Arnold Schwarzenegger
Governor

XONON ULTRA LOW-NOX COMBUSTION APPLIED TO MULTI-COMBUSTOR GAS TURBINES

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
CATALYTICA ENERGY SYSTEMS, INC.

November 2005
CEC-500-2005-174

Prepared By:
Catalytica Energy Systems, Inc.
Tim Caron, Steve Lemons, Sam Nickolas
Phil Tuet, Graydon Whidden
Gilbert, Arizona
Contract No. 500-01-030

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER)
Program

John Henry Beyer, Ph.D
Contract Manager

Arthur J. Soinski, Ph.D.
Environmentally Preferred Advanced Generation Program Area Team Lead

Martha Krebs, Ph. D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B.B. Blevins
Executive Director

Acknowledgement

The authors would like to express thanks and appreciation to Dr. John Henry Beyer of the California Energy Commission for his thoughtful support and encouragement throughout this project.

Catalytica Energy Systems, Inc. 2005. *Xonon Ultra Low-NOx Combustion Applied to Multi-Combustor Gas Turbines.* California Energy Commission, PIER Environmentally Preferred Advanced Generation Research, Contract 500-01-030.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

Pier funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Ultra Low-NOx Combustion project, Energy Commission Contract 500-01-30, conducted by Catalytica Energy Systems, Inc. This report is entitled *Xonon Ultra Low-NOx Combustion in Multi-can Engines Final Report.* This project contributes to the Environmentally-Preferred Advanced Generation Program.

For more information on the PIER Program, please visit the Energy Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Energy Commission's Publications Unit at 916-654-5200.

Table of Contents

List of Figures

List of Tables

Abstract

Catalytica Energy Systems Inc. (CESI) is developing a novel catalytic combustion process that produces ultra-low emissions for natural gas fired turbine engines. As part of this effort, the California Energy Commission sponsored this project whose main goal is to extend the application of catalytic combustion from engines with a silo type combustion system configuration, to gas turbines with a multiple combustor or "multi-can" configuration. The project was divided into two main phases. In the first phase, CESI's technology was modified to enhance its applicability to multi-can engines. The second phase would consist of the design work for a specific engine application, and testing of the system on an actual engine. At the end of the first phase, an Original Equipment Manufacturer (OEM) would join CESI to proceed as partners into the engine application phase.

While the technology phase was completed successfully, CESI was unable to obtain a partner for the engine application phase of the program. As a result, CESI and the Energy Commission have agreed that the project should not proceed into the second phase.

Even though the project has ended prematurely, the technical accomplishments of Phase 1 are significant and indicate that the application of Xonon to multi-can engines is feasible. Xonon combustion system size reductions, performance improvements, and advances in control system approaches are some of the key developments realized from this work.

Executive Summary

Catalytica Energy Systems Inc. (CESI) is developing a novel catalytic combustion process that produces ultra-low emissions for natural gas fired turbine engines. As part of this effort, the California Energy Commission (the Energy Commission) sponsored this project whose main goal is to extend the application of catalytic combustion from engines with the current silo type configuration, to gas turbines with a multiple combustor or "multi-can" configuration. The project was divided into two main phases. In the first phase the new technology required for the application to multi-can engines was developed. The second phase would consist of the design work for a specific engine application and testing of the system on an actual engine. At the end of the first phase, an Original Equipment Manufacturer (OEM) would join CESI to proceed as partners into the engine application phase. The project was structured in this way so that the high-risk technology development portion of the project would be completed prior to the OEM joining the program. This would make the project more attractive and improve the chance of success in finding an OEM willing to work on a Xonon application since the risks associated with developing a technology that has never been used on a multi-can engine would be borne by CESI and the Energy Commission.

While the technology phase was completed successfully, CESI has been unable to obtain a partner for the engine application phase of the program. As a result, CESI and the Energy Commission have agreed that the project should not proceed into the second phase.

This report documents the work that has been completed and discusses the issues that led to the early termination of the project.

Background and Overview

The high temperatures in typical combustion processes accelerate the formation of noxious oxides of nitrogen (NOx). It is well known that NOx formation increases dramatically when the temperature exceeds about 1600°C (2900°F). Traditional diffusion type combustor flame temperatures can exceed 2200°C (4000°F) for brief periods; so it is virtually impossible to achieve ultra-low NOx levels when a turbine is fired with a diffusion flame combustor. State-of-the-art Dry Low NOx (DLN) combustion systems can operate at NOx levels in the high single digits of parts per million by volume (ppmv); however, these systems are expensive and susceptible to flame-out or flame instability because they operate at very low fuel/air ratios near the lean limit. DLN combustion systems will need to be coupled with expensive exhaust cleanup systems in order to achieve NOx levels below 3 ppmv.

The catalytic combustion technology pioneered by CESI (called Xonon®) achieves ultra-low emission levels without the drawbacks found in other low emission technologies. In the Xonon combustion system, NOx formation is reduced as the result of low combustion temperatures. The maximum combustor exit temperatures on a typical small Xonon equipped turbine engine is 1350°C (2460°F) or lower – well below the temperatures where NOx readily forms.

A typical Xonon combustion system is shown in Figure 1. Engine compressor discharge air enters an annular plenum prior to entering the pre-burner. The pre-burner is a small DLN type combustor that pre-heats the combustor air up to the catalyst operating temperature. Fuel is then injected into the warm air and thoroughly mixed before entering the catalyst module. In the catalyst module, some of the fuel/air mixture is combusted through a flameless catalytic process. The combustion process continues in the burnout zone until all of the remaining un-combusted fuel is reacted.

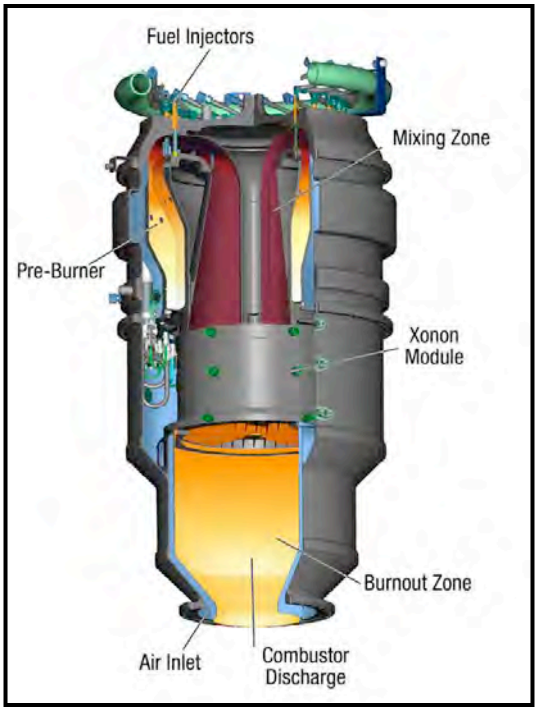


Figure 1 Typical Xonon combustion system

However, catalytic combustion technology as it is currently developed is limited in application to a relatively small family of engines that utilize, or can reasonably be modified to utilize, the external, silo type combustor. Today such systems are confined to relatively small, lower to mid-efficiency range machines principally due to the efficiency-robbing cooling requirements of the "scroll" type transition duct used to feed the combustion products to the turbine section of the engine. The large majority of gas turbines rated over 5 MW, as well as many smaller machines, use either annular combustion systems or a multiple combustor "multi-can" configuration. In both configurations the combustion system is principally contained within the engine's pressure case and employs multiple fuel nozzles to introduce and mix the fuel for combustion.

These two characteristics, the need to fit the catalytic combustion system within the existing pressure case and the necessity to employ multiple "burners"—which gives rise to complex control issues in a can-annular arrangement—are the yet to be developed aspects which have prevented the Xonon technology from being deployed in units which can address the vast majority of the market. This project is aimed at addressing these barriers for the predominant configuration, the multi-can system.

Project Approach
Overall Strategy

CESI's extensive and successful experience with development and field trials of the single-combustor system has served to emphasize the importance of an orderly program which:

- Begins with conceptualization of design features for the principal components
- Uses computerized analytical techniques to refine the preliminary designs and integrate the components
- Proceeds to rig testing of sub-systems where the analysis indicates the need for further refinement, and
- Culminates in a full-scale engine test under real world conditions providing verification of the solutions that will convince the market that the technology is ready for commercialization

This project was divided into the following two phases:

<u>Phase 1 Approach</u>

The initial task in Phase 1 was to identify and quantify the issues and technology gaps that arise when a gas turbine has more than one catalytic combustor. The anticipated issues included geometric constraints for component packaging, pressure losses in the components, and combustor-to-combustor variations of air and fuel flow. Such issues are common to most multi-combustor gas turbines so they could be addressed generically in the early assessments. Advancements in catalyst technology were also pursued such as the ability to operate with smaller catalyst module size, lower pressure drop, and higher gas velocities that can provide flexibility in dealing with the challenges of combustor development.

The next step was to develop approaches for addressing the identified technical challenges. Each issue was characterized both for its likelihood of occurrence and for the severity of its potential impact on engine performance. In this way, the project resources could be directed at the highest priority (high likelihood and high impact) issues. The conceptual solutions relied upon existing, proven technical approaches when possible and creation of new enabling technologies when necessary. The expectation was that a range of options would be generated for resolving each issue.

The project team then developed a means of validating and confirming the suitability of each of the identified options. The techniques employed for validating the various approaches included things such as detailed computational fluid dynamics modeling, and full pressure (subscale) rig testing. To the extent that the feasibility of a particular approach depended upon achieving certain catalyst performance characteristics, catalyst design and testing activities were initiated at this point in the project.

As the preferred strategies and technologies were determined for addressing the issues of multi-combustor gas turbines, CESI entered into discussions with original equipment manufacturers of small, multi-combustor gas turbines to determine which commercial turbine model to pursue for an engine demonstration.

A Critical Project Review was held at the end of Phase 1 to evaluate the findings and implications of the Phase 1 work and to document the commitment of the OEM to the satisfaction of the Energy Commission before CESI could commence work on Phase 2.

Phase 2 Approach

The second phase of the project was to be directed at an engine demonstration. The OEM would have the lead role in defining hardware configurations and test protocols appropriate for developing this engine into a market-ready product using catalytic combustion to achieve ultra-low emissions. CESI would have responsibility for the catalyst system and its performance, developing and supplying the catalyst modules, and supporting the multi-combustor turbine development effort. CESI's unique experience in designing, building, and operating a catalytic combustor on a grid-connected gas turbine would be an important asset in supporting the OEM's development effort.

The Phase 2 tasks were to be organized around three activities: system design, component development, and engine demonstration. These were to be sequential efforts, although there would be overlap among them in order to optimize the timeline for the overall project. For example, rig testing of one component could begin while another component was still in the design stage. Likewise, procurement of certain engine hardware could begin while options for other hardware are still being evaluated in rig tests. The intention was to take every opportunity to accelerate the project without incurring undue risk. Project execution was to be arranged as follows:

System Design

CESI was to work closely with the OEM to integrate the Xonon combustion system into the particular multi-can turbine platform that is selected. The initial efforts in this area would be to focus on the design specifications, component sizing, and general mechanical arrangement of the various system components on the engine. Then the catalyst requirements were to be broadly defined; and, on this basis, CESI would undertake a statistically based catalyst design process using in-house catalyst test facilities. The catalyst module development was also to include mechanical design and structural analyses for the catalyst container.

The OEM was to assume the lead role in the mechanical design, integration, test development, and optimization of the combustion system components other than the catalyst module. The key components for which CESI was to provide technical support include the preburner, the fuel-air mixing section, the catalyst module, and the post-catalyst homogeneous combustion zone. The design support envisioned in this task was expected to include establishing the optimal component and system configuration, component sizing, mechanical integration, and analytical evaluation. CESI would also have assisted the manufacturer in developing an effective controls algorithm to accommodate all facets of turbine operation – normal startup, shutdown, and loading sequences as well as sudden events such a turbine trips.

Component Development

Subsequent to the design and analysis activities just described, certain aspects of component performance could only be determined by experimentation. Such testing was to be done using prototype versions of the component(s) under investigation. CESI was to design and supply the necessary catalyst modules. On the basis of successful previous development of components for the single-combustor turbine, CESI could support the OEM's testing by specifying critical instrumentation, verifying the suitability of the test conditions, critiquing the test plan, monitoring test execution, and assisting in assessing the implications of the test data. Normally, the first tests of novel components result in iterations through re-design – the prospect of such events was anticipated in the project schedule.

Engine Demonstration

The final technical element of Phase 2 was to be an engine operating with multiple catalytic combustors and delivering ultra-low emissions. CESI's primary responsibility for this engine demonstration was to provide the catalyst modules in a robust mechanical configuration suitable for commercial installation. Additionally, CESI was to participate in planning and executing the engine test, with particular attention to the behavior of the controls system in managing the preburner and fuel/air distribution systems to optimize catalyst performance.

Project Outcome

At the conclusion of Phase 1 CESI had not found an OEM willing to invest in the application phase of the project which involved fielding an engine with a multi-can Xonon system installed and ready for trial. The project plan included a critical project review to be held at the completion of Phase 1. At this review, CESI and the Energy Commission agreed to terminate the project.

Technical Outcome

The technical objectives in Phase 1 were successfully completed with the following accomplishments:

- 31 % reduction in combustion system length for the multi-can configuration versus the silo configuration
- Preliminary design of a high performance high turndown ratio preburner
- Engine control system improvements to address controls issues related to operating multiple combustion systems in a multi-can engine
- Catalyst manufacturing yield improvement of 9%

Outcome of OEM Discussions

After extensive discussions with many potential OEM's an analysis of the situation yielded three main reasons why CESI could not find an OEM partner willing to work on a product directed toward the distributed generation (DG) market with its strict emissions requirements:

- Recession of 2001 and subsequent energy glut
- High natural gas prices
- Perception that low emissions regulations are a local phenomenon that will not be widely adopted by regulatory agencies

Recession of 2001 and subsequent energy glut

The economic environment that existed prior to the beginning of this project was one of economic growth and soaring energy demand. This was especially true in Silicon Valley where for the first time in memory rolling electrical blackouts occurred as utilities were grappling with the energy needs demanded by a growing economy in the midst of a stock market bubble. At the time, it was widely believed that DG had the potential to play a major role in resolving the energy crises if low emissions solutions could be quickly developed.

After the post 9/11 recession of 2001, electricity demand declined to levels that were easily met by the then existing electrical generating infrastructure. The makers of electrical generating equipment, most notably the gas turbine manufacturers, were in financial distress as large numbers of engine orders were canceled with the decline in electricity demand. Amidst these negative business conditions, CESI found that OEMS were not inclined to invest in new technology but were instead retrenching their businesses and trying to strengthen their balance sheets.

<u>High natural gas prices in 2005</u>

High natural gas prices have also worked to reduce the attractiveness of DG for peaking applications. When gas is expensive, the economics of electricity generation provide an incentive to produce power from the most efficient generating assets available or from the cheapest fuel source. For natural gas, the most efficient units are the large, centrally located, combined cycle power plants

<u>Perception that low emissions regulations are a local phenomenon that will not be widely adopted by regulatory agencies</u>

Some gas turbine manufacturers expressed the view that the very low emissions requirements targeted by this project are not a broad market requirement but instead are unique to specific areas of California and the Northeast United States. This view makes it hard for them to justify the expense of developing a low emissions product that may end up targeting a relatively small portion of the market.

All of these factors have combined to inhibit the growth of the DG market, and have reduced the incentive for the equipment manufacturers to invest in enhancements to their small multi-can gas turbines that were targeted for DG application.

Production Readiness

CESI has put in place significant resources over the last several years to meet the projected production demands for Xonon catalyst modules. The company has opened a new facility in Gilbert, Arizona, for the manufacture and assembly of Xonon modules. The facility is sized to meet the production demand for at least the next 5-7 years.

Conclusion

The primary goal of this project was to extend the application of Xonon to multi-can engine applications. The first phase of the project, in which the enabling technology was developed, has been successfully completed. However, the second phase, which was the engine application portion of the effort, was not completed. After a critical project review prior to commencement of the second phase, CESI and the Energy Commission agreed to halt work on the project. The primary reason for this decision was that CESI was unable to recruit a manufacturer of multi-can gas turbines to join the project for the application phase. After discussions with various original equipment manufacturers CESI determined that the economic and market environment that existed during the course of the project was a detrimental factor contributing to their decisions to not participate.

While the project has ended prematurely, the technical accomplishments of Phase 1 are significant and indicate that the application of Xonon to multi-can engines is feasible. Xonon combustion system size reductions, performance improvements, and advances in control system approaches are some of the key developments realized from this work. CESI hopes that the Xonon technology will yet find its way into multi-can engine applications.

Another accomplishment of the project is the potential yield improvement for the manufacturing process while at the same time increasing product quality. This benefit is directly applicable to the current production of catalyst modules for the Kawasaki M1A-15X which uses the silo-type combustion system configuration. This system is currently operating in California at two sites, with a third under construction.

1.0 Introduction

1.1. Background and Overview

The goal of this project was to develop a catalytic combustion system for achieving ultra-low emissions in small, multi-combustor gas turbines without the need for exhaust gas cleanup devices.

The high temperatures in typical combustion processes accelerate the formation of noxious oxides of nitrogen (NOx). It is well known that NOx formation increases dramatically when the temperature exceeds about 1600°C (2900°F). Traditional diffusion flame combustor flame temperatures can exceed 2200°C (4000°F) for brief periods; so it is virtually impossible to achieve ultra-low NOx levels when a turbine is fired with a diffusion flame combustor. State-of-the-art combustion systems can operate at NOx levels in the high single digits of parts per million by volume (ppmv), however, these systems are expensive and susceptible to flame-out or flame instability because they operate at very low fuel/air ratios near the lean limit. DLN combustion systems will need to be coupled with expensive exhaust cleanup systems in order to achieve NOx levels below 3 ppmv.

The catalytic combustion technology pioneered by CESI achieves ultra-low emission levels without the drawbacks found in other low emission technologies. In the Xonon combustion system, NOx formation is reduced as the result of low combustion temperatures. The maximum combustor exit temperatures on a typical small Xonon equipped turbine engine is 1350°C (2460°F) or lower – well below the temperatures where NOx readily forms.

A typical Xonon combustion system is shown in Figure 2. Engine compressor discharge air enters an annular plenum prior to entering the pre-burner. The pre-burner is a small DLN type combustor that pre-heats the combustor air up to the catalyst operating temperature. Fuel is then injected into the warm air and thoroughly mixed before entering the catalyst module. In the catalyst module, the some of fuel/air mixture is combusted through a flameless catalytic process. The combustion process continues in the burnout zone until all of the remaining un-combusted fuel is reacted.

The current emissions requirement for permitting a new gas fired turbine in California is generally under 9 ppm NOx, with significantly more stringent requirements (< 5 ppm) found in the San Francisco Bay Area and in the South Coast Air Quality District. The current marketplace method for achieving these levels involves the use of a Selective Catalytic Reduction (SCR) unit of about 95% reduction to achieve ~ 9 ppm NOx. For levels below 9 ppm NOx, the SCR unit must be used in conjunction with an additional method of control (e.g. steam injection, lean pre-mix combustion technology). These stringent emission requirements pose significant cost burdens on power generators. Catalytic combustion, which is a pollution prevention technology, has the potential to significantly reduce the cost over that of the current state-of-the-art cleanup technologies.

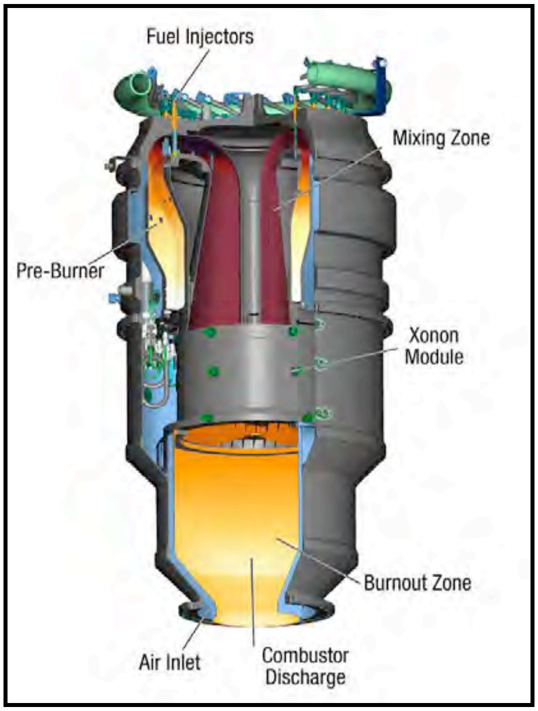


Figure 2 Typical Xonon combustion system

The scientific and engineering communities have recognized catalytic combustion for almost thirty years as a technically compelling approach to reducing NOx emissions in gas turbines. Previous efforts at developing robust catalytic combustors for gas turbines have achieved low, single-digit NOx ppm levels but have failed to produce combustion systems with suitable operating lifetimes. This was typically due to the lack of suitable high-temperature materials used for catalysts and associated catalyst support systems.

Catalytic combustors provide an economically attractive alternative, as compared to exhaust gas clean-up technologies, for the full range of gas turbine sizes. This is especially true for small turbines, which are expected to provide a considerable amount of electrical power in the distributed generation market. Before commercial acceptance, however, catalytic combustion systems need to demonstrate the reliability, availability, maintainability and durability required of modern power generation gas turbine systems.

1.2. Project Objectives

Catalytic combustion technology as it is currently developed has limited application to a relatively small family of engines which utilize, or can reasonably be modified to utilize, the external, silo type combustor. Today such systems are confined to relatively small, lower to mid-efficiency range machines, principally due to the efficiency-robbing cooling requirements of the "scroll" type transition duct used to feed the combustion products to the turbine section of the engine. The large majority of gas turbines rated over 5 MW, as well as many smaller machines, use either annular combustion systems or a multiple combustor "multi-can" configuration. In both configurations the combustion system is principally contained within the engine's pressure case and employs multiple fuel nozzles to introduce and mix the fuel for combustion.

These two characteristics, the need to fit the catalytic combustion system within the existing pressure case and the necessity to employ multiple "burners"—which gives rise to complex control issues in a can-annular arrangement—are the yet to be developed aspects which have prevented the Xonon technology from being deployed in units which can address the vast majority of the market. This proposal is aimed at addressing these barriers for the predominant configuration, the multi-can system. This must be accomplished while assuring attractive economics. The economics being driven by factors including catalyst module life, system operation and maintenance cost, reliability and system initial cost.

This project meets the PIER objective of *improving the environmental and public health costs/risks of California's electricity* by enabling attainment of the EPAG Stretch Goals for emissions levels without the need for exhaust cleanup systems.

This project also meets the secondary goal of *improving the energy cost/value of California's electricity* by enabling use of small gas turbines for distributed generation in situations where the cost and footprint requirements of exhaust cleanup systems to meet the mandated emissions levels would be prohibitive.

The overall technical objective of this project was to *conduct a successful engine test of the ultra-low emissions technology* using a small gas turbine model that is currently marketed commercially. The performance objective is exhaust NOx, CO, and UHC levels (at 15% O_2) below 3 ppm, 10 ppm, and 10 ppm, respectively, at simulated loads from 80% to 100% of the turbine's rated power output.

The overall economic/cost objective of this project is to *develop a catalytic combustion system that is economically preferred over all other options* for achieving exhaust NOx levels below 3 ppm in a small, multi-combustor gas turbine.

This project supports the mission of the PIER Program by focusing on developing an *environmentally attractive, safe, reliable, and affordable technology for generating electricity* wherever it is needed by California's citizens. The technology has been demonstrated successfully on a single-combustor gas turbine, but the technical challenges and associated economic risks of extending the technology to multi-combustor engines have been barriers to its wider adoption and availability to the distributed generation market. *PIER funding was seen as the enabling resource* in addressing and overcoming those barriers.

2.0 Project Approach

2.1. Overall Strategy

CESI's extensive and successful experience with development and field trials of the single-combustor system has served to emphasize the importance of an orderly program which:

Begins with conceptualization of design features for the principal components

Uses computerized analytical techniques to refine the preliminary designs and integrate the components

Proceeds to rig testing of sub-systems where the analysis indicates the need for further refinement, and

Culminates in a full-scale engine test under real world conditions providing verification of the solutions that will convince the market that the technology is ready for commercialization

This project is divided into the following two phases:

2.2. Phase 1 Approach

The initial task in Phase 1 was to identify and quantify the issues and technology gaps that arise when a gas turbine has more than one catalytic combustor. The anticipated issues included geometric constraints for component packaging, pressure losses in the components, and combustor-to-combustor variations of air and fuel flow. Such issues are common to most multi-combustor gas turbines so they could be addressed generically in the early assessments. It was likely that advancements in catalyst technology would be desirable as well – the ability to operate with smaller catalyst module size, lower pressure drop, and higher gas velocities can provide flexibility in dealing with the other challenges of combustor development. Thus, catalyst development was also part of the Phase 1.

The next step was to develop approaches for addressing the identified technical challenges. Each issue was characterized both for its likelihood of occurrence and for the severity of its potential impact on engine performance. In this way, the project resources were directed at the highest priority (high likelihood and high impact) issues. The conceptual solutions relied upon existing, proven technical approaches when possible and creation of new enabling technologies when necessary. The expectation was that a range of options would be generated for resolving each issue.

The project team then developed a means of validating and confirming the suitability of each of the identified options. The techniques employed for validating the various approaches included things such as detailed computational fluid dynamics modeling, and full pressure (subscale) rig testing. To the extent that the feasibility of a particular approach depended upon achieving certain catalyst performance characteristics, catalyst design and testing activities were initiated at this point in the project.

As the preferred strategies and technologies were determined for addressing the issues of multi-combustor gas turbines, CESI entered into discussions with original equipment manufacturers of small, multi-combustor gas turbines to determine which commercial turbine model to pursue for an engine demonstration.

A Critical Project Review was held at the end of Phase 1 to evaluate the findings and implications of the Phase 1 work and to document the commitment of the OEM to the satisfaction of the Energy Commission before CESI could commence work on Phase 2.

2.3. Phase 2 Approach

The second phase of the project was to be directed at an engine demonstration. The OEM would have the lead role in defining hardware configurations and test protocols appropriate for developing this engine into a market-ready product using catalytic combustion to achieve ultra-low emissions. CESI would have responsibility for the catalyst system and its performance, developing and supplying the catalyst modules, and supporting the multi-combustor turbine development effort. CESI's unique experience in designing, building, and operating a catalytic combustor on a grid-connected gas turbine would be an important asset in supporting the OEM's development effort.

The Phase 2 tasks were to be organized around three activities: system design, component development, and engine demonstration. These were to be sequential efforts, although there would be overlap among them in order to optimize the timeline for the overall project. For example, rig testing of one component could begin while another component was still in the design stage. Likewise, procurement of certain engine hardware could begin while options for other hardware are still being evaluated in rig tests. The intention was to take every opportunity to accelerate the project without incurring undue risk. Project execution was to be arranged as follows:

2.3.1. System Design

CESI was to work closely with the OEM to integrate the Xonon combustion system into the particular multi-can turbine platform that is selected. The initial efforts in this area would be to focus on the design specifications, component sizing, and general mechanical arrangement of the various system components on the engine. Then the catalyst requirements were to be broadly defined; and, on this basis, CESI would undertake a statistically based catalyst design process using in-house catalyst test facilities. The catalyst module development was also to include mechanical design and structural analyses for the catalyst container.

The OEM was to assume the lead role in the mechanical design, integration, test development, and optimization of the combustion system components other than the catalyst module. The key components for which CESI was to provide technical support include the preburner, the fuel-air mixing section, the catalyst module, and the post-catalyst homogeneous combustion zone. The design support envisioned in this task was expected to include establishing the optimal component and system configuration, component sizing, mechanical integration, and analytical evaluation. CESI would also have assisted the manufacturer in developing an effective controls algorithm to accommodate all facets of turbine operation – normal startup, shutdown, and loading sequences as well as sudden events such a turbine trips.

2.3.2. Component Development

Subsequent to the design and analysis activities just described, certain aspects of component performance could only be determined by experimentation. Such testing was to be done using prototype versions of the component(s) under investigation. CESI was to design and supply the necessary catalyst modules. On the basis of successful previous development of components for the single-combustor turbine, CESI could support the OEM's testing by specifying critical instrumentation, verifying the suitability of the test conditions, critiquing the test plan, monitoring test execution, and assisting in assessing the implications of the test data. Normally, the first tests of novel components result in iterations through re-design – the prospect of such events was anticipated in the project schedule.

2.3.3. Engine Demonstration

The final technical element of Phase 2 was to be an engine operating with multiple catalytic combustors and delivering ultra-low emissions. CESI's primary responsibility for this engine demonstration was to provide the catalyst modules in a robust mechanical configuration suitable for commercial installation. Additionally, CESI was to participate in planning and executing the engine test, with particular attention to the behavior of the controls system in managing the preburner and fuel/air distribution systems to optimize catalyst performance.

3.0 Project Outcome

At the conclusion of Phase 1 CESI had not found an OEM willing to invest in the application phase of the project which involved fielding an engine with a multi-can Xonon system installed and ready for trial. The project plan included a critical project review to be held at the completion of Phase 1. At this review, CESI and the Energy Commission agreed to terminate the project.

3.1. Technical Outcome

The technical objectives in Phase 1 were successfully completed with the following accomplishments:

31 % reduction in combustion system length for the multi-can configuration versus the silo configuration.

Preliminary design of a high performance high turndown ratio pre-burner.

Engine control system improvements to address controls issues related to operating multiple combustion systems in a multi-can engine.

Catalyst Manufacturing yield improvement of 9%.

3.2. Outcome of OEM Discussions

After extensive discussions with many potential OEM's an analysis of the situation yielded three main reasons why CESI could not find an OEM partner willing to work on a product directed toward the distributed generation (DG) market with its strict emissions requirements:

- Recession of 2001 and subsequent energy glut
- High natural gas prices
- Perception that low emissions regulations are a local phenomenon that will not be widely adopted by regulatory agencies

Recession of 2001 and subsequent energy glut

The economic environment that existed prior to the beginning of this project was one of economic growth and soaring energy demand. This was especially true in Silicon Valley where for the first time in memory rolling electrical blackouts occurred as utilities were grappling with the energy needs demanded by a growing economy in the midst of a stock market bubble. At the time, it was widely believed that DG had the potential to play a major role in resolving the energy crises if low emissions solutions could be quickly developed.

After the post 9/11 recession of 2001, electricity demand declined to levels that were easily met by the then existing electrical generating infrastructure. The makers of electrical generating equipment, most notably the gas turbine manufacturers, were in financial distress as large numbers of engine orders were canceled with the decline in electricity demand. Amidst these negative business conditions, CESI found that OEMS were not inclined to invest in new technology but were instead retrenching their businesses and trying to strengthen their balance sheets.

High natural gas prices

High natural gas prices have also worked to reduce the attractiveness of DG for peaking applications. When gas is expensive, the economics of electricity generation provide incentive to produce power from the most efficient generating assets available or from the cheapest fuel source. For natural gas, the most efficient units are the large, centrally located, combined cycle power plants

Perception that low emissions regulations are a local phenomenon that will not be widely adopted by regulatory agencies

Some gas turbine manufacturers expressed the view that the very low emissions requirements targeted by this project are not a broad market requirement but instead are unique to specific areas of California and the Northeast United States. This view makes it hard for them to justify the expense of developing a low emissions product that may end up targeting a relatively small portion of the market.

All of these factors have combined to inhibit the growth of the DG market, and have reduced the incentive for the equipment manufacturers to invest in enhancements to their small multi-can gas turbines that were targeted for DG application.

3.3. Production Readiness

Introduction

Even though the project was ended early this production readiness plan is included in this report because improvements to the manufacturing process of the Xonon catalyst were realized as part of this project.

In managing the PIER Program, the California Energy Commission (the Energy Commission) has a goal of bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. In pursuit of this goal, the Energy Commission requires that Contractors who receive PIER funding deliver a Production Readiness Plan that describes the proposed manufacturing processes, capabilities, constraints, and timing to achieve a commercially viable product. The degree of detail in the Plan should be directly related to the complexity of producing the proposed product and its state of development. That is, the more complex the process and the closer it is to being market-ready, the more important it is that the Energy Commission has the information to assess its viability for bringing products to the marketplace.

The product manufactured by CESI to achieve ultra-low emissions from gas turbines is the Xonon catalyst module. For the Xonon module:

- The production process is relatively simple
- Development and optimization of the process have been ongoing for over ten years
- The equipment configuration and critical steps in the commercial production process were proven more than eight years ago

- The first commercial Xonon catalyst modules were produced for shipment in August 2001 – the process works. Modules are manufactured in response to sales of the associated Xonon-equipped turbines

Several turbine components besides the catalyst module must be specially designed to assure the effectiveness of the Xonon combustion system. While CESI typically works in partnership with each turbine manufacturer to design such key components as the preburner, the fuel-air mixer, the air staging system, and the necessary controls system, the manufacturer is responsible for the final design, manufacturing, and performance of those components.

Manufacturing Overview

A Xonon catalyst module consists of the catalyst itself and the surrounding container. An example is shown schematically in Figure 3. The catalyst stage is typically a cylindrical shape with a diameter of from 8 inches to more than 28 inches and a thickness (height) of 2 inches to 5 inches. The unit in Figure 3 is a single stage module; but, depending upon the application, the optimal system design can consist of 1, 2 or 3 catalyst stages stacked within a single container. The container must be designed: 1) to maintain the physical position of the catalyst against the aerodynamic forces of the combustor gas flow, and 2) to seal the catalyst perimeter against gas leakage during the thermal and flow transients of turbine operation.

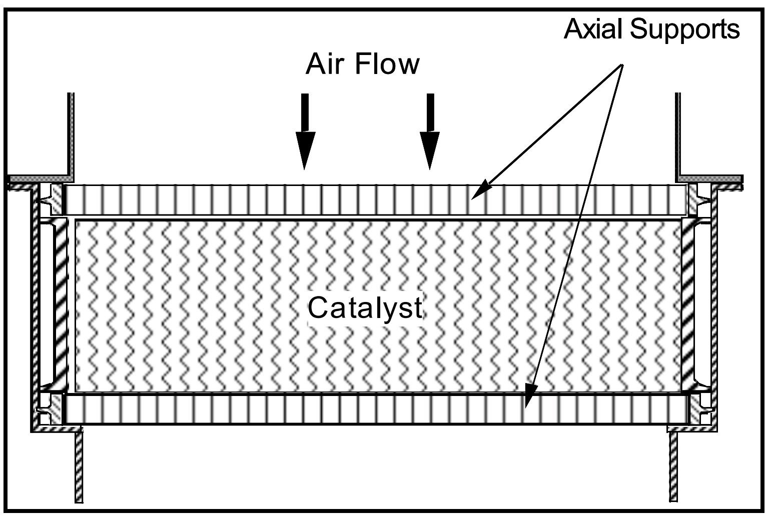


Figure 3 Schematic diagram of the catalyst module with axial support structures at inlet and outlet

CESI has a new manufacturing operation in Gilbert, Arizona, that produces the catalyst modules for the commercial Kawasaki 1.4 megawatt M1A-13X gas turbines. The catalyst material is manufactured in-house solely by CESI. The mechanical parts of the container are designed by CESI, fabricated by outside vendors, and assembled at the CESI facility. The manufacturing process for the catalyst itself has been under development and refinement for over ten years. The currently proven and available production capacity will be adequate to support the initial commercial demands for Xonon equipped turbines.

CESI has attained ISO 9001 registration for its catalyst manufacturing operation and the associated quality assurance procedures. The Gilbert site is located in Hewson Development Corporation's Fiesta Tech Centre in Gilbert, Arizona, at 1388 N. Tech Boulevard. The 43,472 square-foot facility houses various administrative functions as well as the Company's Engineering Center and its commercial manufacturing operations.

Production Capacity

There are no significant capacity constraints in CESI's current production systems. Moreover, the modular design of the CESI catalyst manufacturing operation allows for expansion of capacity when the need arises. Larger equipment and the associated issues of equipment redesign and testing are not needed to achieve an increase in Xonon catalyst production volume. Production capacity is a matter only of throughput rate, not of equipment size. Thus, capacity can be added simply by installing a replicate of the grouping ("cell") of already proven machines. This is reflected in the floor plan shown in Figure 4. When the business requires further expansion of production, CELL 2 and then CELL 3 can be installed and brought on line.

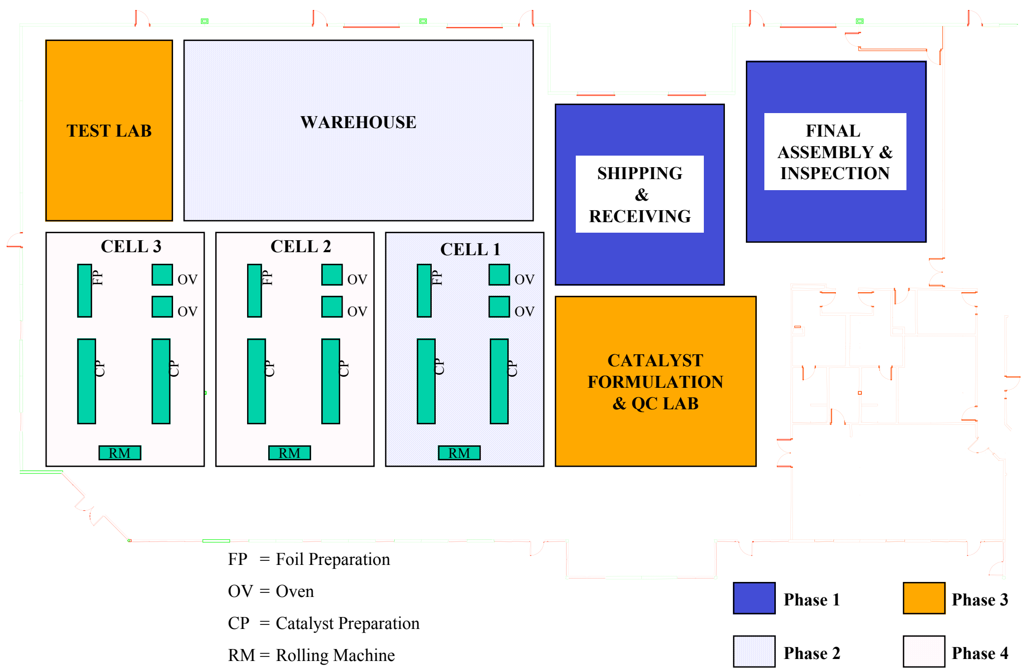


Figure 4 Floor plan of Catalytica Energy Systems manufacturing facility in Gilbert, Arizona

4.0 Technical Discussion

4.1. Technical Approaches Validation

4.1.1. Introduction

This section documents the technical approaches validation portion of the project. The goals of this task were to (1) develop conceptual approaches for resolving technical issues associated with the application of Xonon to small multi-can gas turbines, and (2) validate each approach by a suitable technical means.

4.1.2. Approach

Three categories of technical issues were identified in this project. They include:

System Size
Performance
Controls

The issues were identified as a result of two packaging studies performed on small (<20 MW) multi-combustor gas turbine engines. The engines selected for the packaging studies were natural gas fired turbines primarily used in either a simple cycle power generation or co-generation mode.

Solutions addressing each technical issue were developed and then validated.

4.1.3. System Size

Combustion system size emerged as a technical issue due to clearance constraints imposed on individual can installation and removal when conventional Xonon technology is applied. In particular, installation of the lower combustor can becomes difficult due to the proximity of the under engine support frame and the ground itself. Reducing the overall length of the Xonon system would improve clearances, simplify installation and improve handling characteristics. To address and resolve the size issue and improve Xonon system packaging, each of the components that contribute to the overall system length were examined for size reduction potential. Components that contribute most directly to the overall length of the Xonon system include the catalyst fuel-air pre-mixer, the catalyst module itself and the post catalytic combustion burn-out zone (BOZ). The technical approach and validation efforts adopted for reducing the size of each component are described below.

4.1.3.1. <u>Premixer Optimization</u>

To facilitate installation and increase removal clearances of the Xonon system, a technology task was established with the stated purpose of reducing the length of the baseline Xonon fuel-air premixer. The task is hereafter referred to as the "Premixer Optimization" task. The specific goal of the task was a diffuser length reduction of at least 25% while maintaining conformance to the standard CESI premixer performance requirements. Typical performance requirements include specification of the limits on allowable spatial variation in the fuel-air ratio (±3%), temperature (±10 ºC) and velocity (±10%) at the catalyst face. Large variations in the flow properties at the face of the catalyst may negatively impact the catalyst operating window and/or engine exhaust emissions.

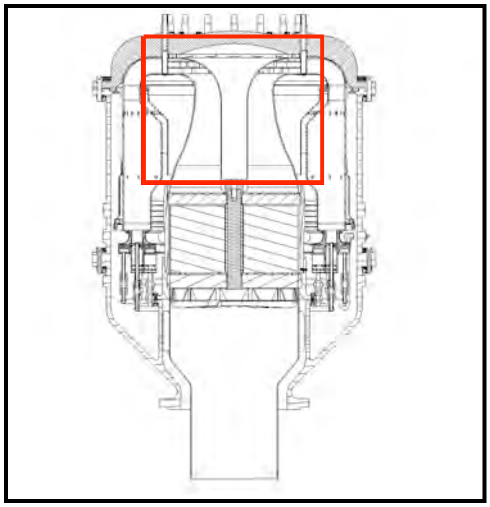


Figure 5 Cross section highlighting location of catalyst fuel-air premixer

Background

The current method employed for catalyst fuel-air preparation in the Xonon system is to rely on distributed fuel injection and rapid mixing through the spread of turbulence generated by high fluid shear rates. The high shear rates are generated by a radial inflow, multi-channel, counter-rotating swirler. Fuel injection is accomplished by injection through a series of fuel pegs located upstream of the swirler. A cross section of a typical Xonon premixing system is shown on the following page for reference.

A significant level of effort is required to "tune" or optimize the swirler vane relative turning angles in conjunction with the flow-path coordinates such that the aerodynamics in the diffusing section are stable and vortex breakdown does not occur. A breakdown in the flow field in the diffusing section is undesirable from several perspectives including potential flame-holding, auto-ignition and/or elevated pressure drop.

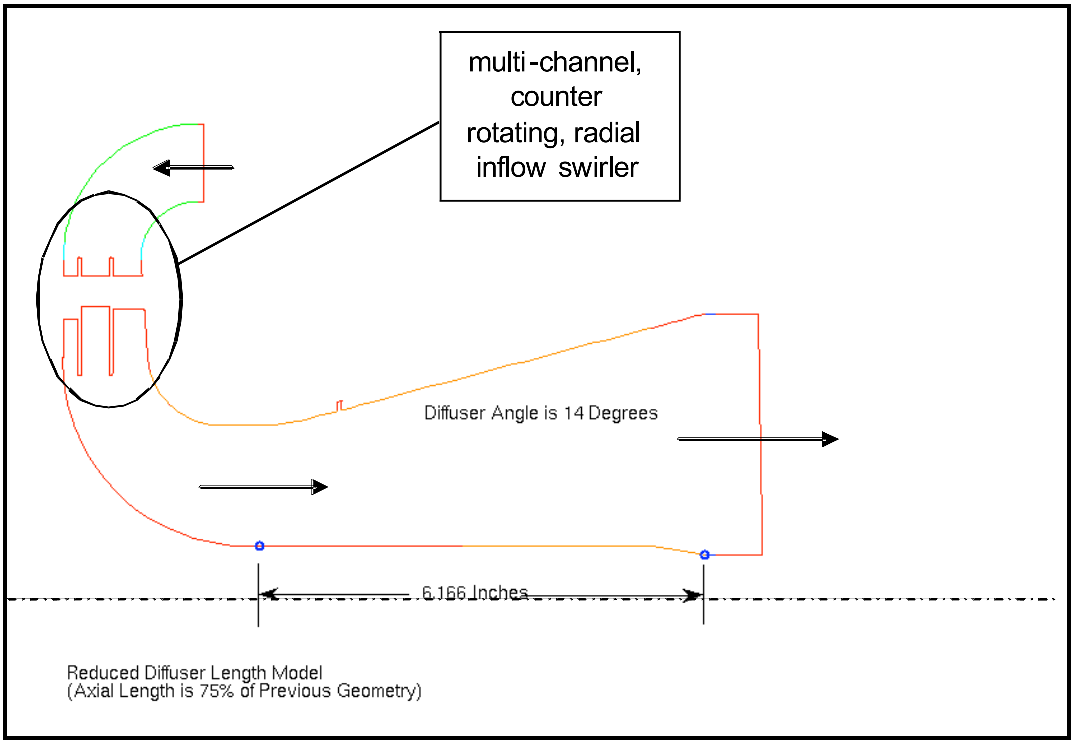


Figure 6 Xonon style radial inflow fuel-air premixer

To quantify the length reduction potential of the pre-mixer, the Computational Fluid Dynamics (CFD) code Star-CD was utilized (version 3.05). To establish a baseline, a simulation of the existing technology Xonon pre-mixer was performed. The baseline then formed the basis upon which follow on length reductions could be measured. The overall objective of the task was to optimize the existing Xonon pre-mixer on the basis of length and thus establish the length reduction potential for a given, fixed level of required performance.

Results

In all, four major flowpath iterations were required prior to making a determination of the shortest possible mixer. The schematic on Figure 7 illustrates the relative downward progression of the pre-mixer size for each major design iteration.

For each design and analysis iteration, a new computational model was created and a mesh was applied. Inlet boundary conditions to the premixer (preburner outlet) were applied based on a reacting flow analysis of a similar preburner previously performed. By applying realistic inlet conditions rather than plug flow conditions, an improved assessment of the real aerodynamic and mixing performance potential of each mixer iteration could be more accurately determined.

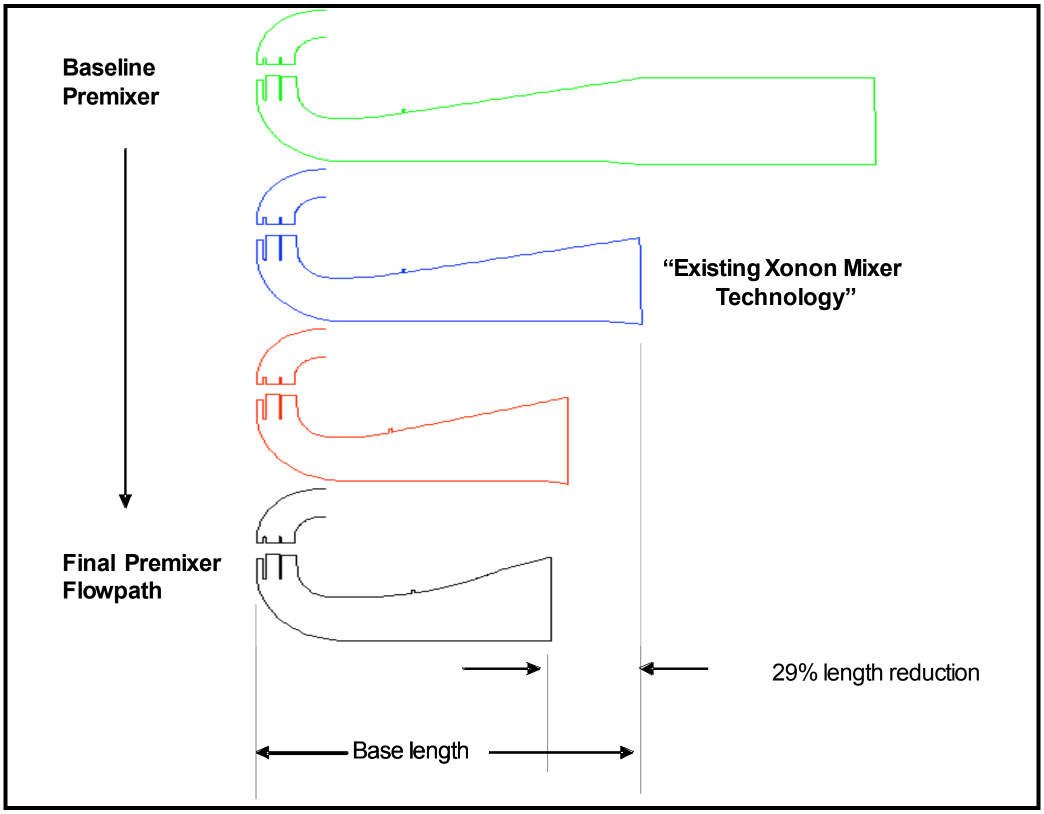


Figure 7 Progression for mixer overall length reduction

Typical technical challenges encountered during the flowpath refinement and size reduction process included flow separation near the outer wall upstream of the catalyst and poor overall fuel-air premixing performance. Flow separation is undesirable from the perspective of flame-holding risk and elevated pressure drop and poor fuel air premixing reduces the size of the catalyst operating window. However, by incorporating appropriate flowpath refinements and fuel injector modifications in each design iteration these issues were successfully addressed prior to proceeding to the next incremental length reduction.

The final flowpath design denoted as *Final Premixer Flowpath* in Figure 7 above, features an overall mixer length reduction of 29% relative to existing Xonon technology. The figures on the following page show representative CFD results for the final pre-mixer flowpath design. The rapid mixing is most evident in Figure 8 below which shows that most of the fuel (shown in red) has mixed out by the time the flow field reaches the throat.

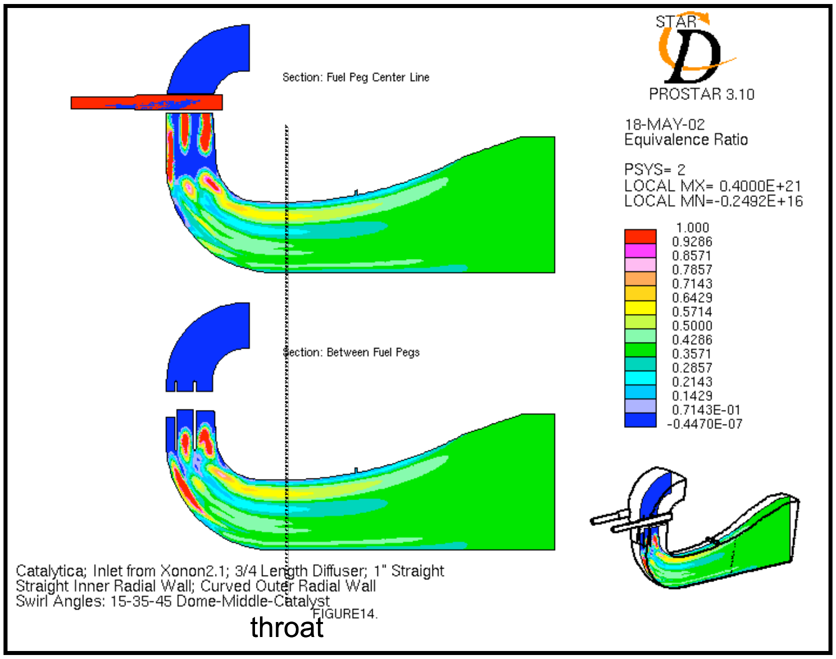


Figure 8 Section views showing the fuel air pre-mixing progression

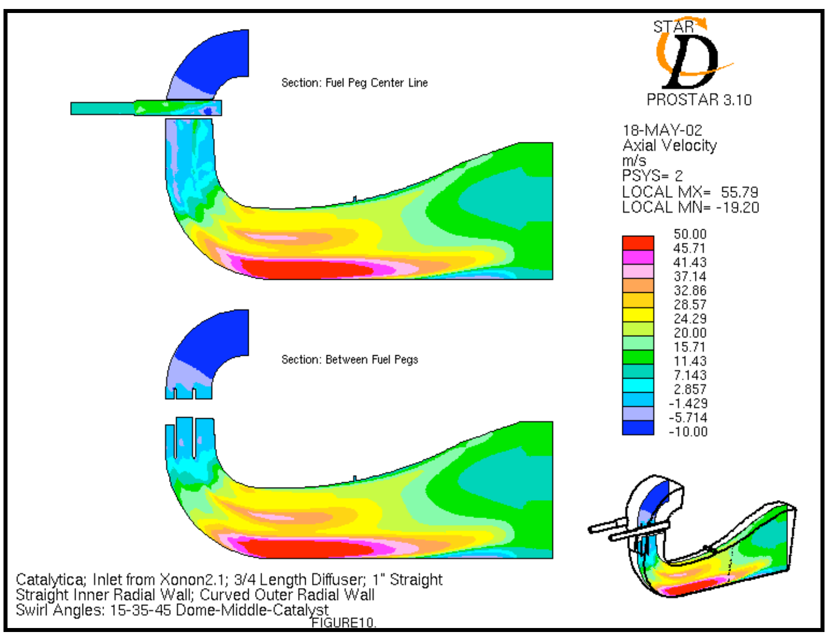


Figure 9 In plane axial velocity contours for final reduced size pre-mixer — Design point operating condition

The pre-mixer optimization task was successful and with a 29% overall length reduction, successfully met the task objective of >25% overall diffuser length reduction while maintaining conformance to the standard catalyst inlet uniformity requirements. A summary of the final performance highlights is listed in the table below.

Parameter	Value	Comments
Overall Length Reduction (%)	29.0	Relative to existing Xonon technology
Contribution to Overall System Length Reduction (%)	8.5%	Task contributes 8.5% of overall length reduction
Catalyst Inlet F/A Uniformity (%)	+1.9/-3.3	Meets objective
Thermal Uniformity (°C)	+1.2/-0.4	Meets objective with large margin
Axial Velocity Variation (%)	+7.7/-9.5	Meets objective
Pressure Drop (%)	<0.50	Meets objective with moderate margin

Table 1 Mixer optimization task results summary

4.1.3.2. Single Stage "E" Class Catalyst

To maximize the overall Xonon system length reduction, the catalyst section was also examined for contributions toward that objective. The catalyst is located downstream of the premixer and upstream of the burnout zone as shown in Figure 10 below.

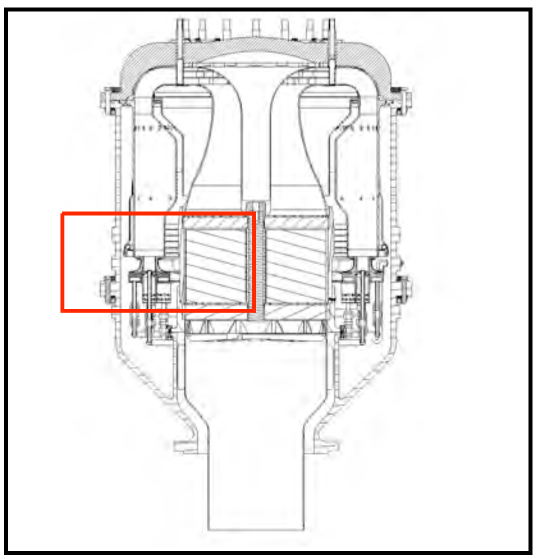


Figure 10 Cross section highlighting location of catalyst module

Background

Traditionally, the standard CESI catalyst design approach for "E" Class firing temperature applications has been to utilize a two-stage approach with a high activity, high surface area inlet stage designed for good light off performance and an outlet stage designed for good thermal stability at higher operating temperatures. The single stage development task initiated under the Multi-Can program thus focused on the elimination of one complete catalyst stage while retaining the critical performance and life characteristics inherent in the standard two-stage design approach. The length reduction potential in going from a two-stage approach to a single stage approach is typically in the range of 35-50% depending on the application being considered.

Results

To successfully develop a reduced length, single stage "E" class catalyst design which simultaneously meets the dual objectives of performance and life, several design parameters and "characteristics" must be considered. A key performance parameter necessary for successful single stage implementation is achieving the required level of overall fuel conversion within the catalyst bed itself prior to exiting the catalyst. Catalyst life is the other important characteristic of a successful single stage design and a catalyst change out interval of 16000 hrs was specified as the target for this program.

The various approaches adopted for the development of a single stage catalyst design concept are listed below.

Analytical evaluation of the impact of individual, standard CESI catalyst design parameters using the "in house" Catalyst Performance and Life Model (CPLM). The objective with this approach was to determine, using the CPLM, whether incorporation of some unique combination of standard CESI catalyst design parameters could be specified which yield (in a single stage) a design approach with sufficiently high conversion.

Supplemental development and high pressure rig test verification of advanced, single stage materials with improved aging characteristics. This approach is more fundamental in nature and required a greater application of resources due to materials development and performance testing.

Fundamental catalyst design modifications. This approach focused on identification and incorporation of fundamental catalyst design changes necessary to meet the performance goal objectives. Catalyst life was not addressed specifically with this approach.

Regarding the first approach described above, a total of 27 individual calculations utilizing the CPLM were conducted. Although parameter groups resulting in increased catalyst conversion were identified based on the analysis, it was determined that perturbations of the standard CESI catalyst design parameters (such as channel height and coating thickness variation) would not be adequate to provide for the performance improvements necessary for a single stage solution. Thus, this approach was not pursued further.

The second approach listed above did prove successful in verifying the improved performance potential and life characteristics of several advanced CESI catalytic material formulations. Those materials are not discussed further here due to their proprietary nature.

The third approach described above proved successful in identifying a potential "E" class single stage design approach. The approach involves manipulation of certain geometry characteristics which in turn result in improved overall conversion levels. Incorporation of advanced material formulations described in approach #2 above along with the catalyst design modifications described in this approach have emerged as the recommended overall best approach for development of a single stage catalytic system.

4.1.3.3. Burnout Zone (BOZ) Size Reduction

The remaining component which contributes to the overall length of the Xonon system is the burnout zone or "post-catalytic combustion zone". The purpose of the burnout zone is to provide the volume necessary for the efficient oxidation of the fuel that is not consumed in the catalyst. Figure 11 below highlights the location of the burnout zone within the overall top level Xonon assembly.

Background

This technology task was initiated with the intent of reducing the size and length of the BOZ by developing a means of enhancing the stability and controllability of the post catalytic homogenous combustion wave. Improving the location control capability of the combustion wave would allow for the elimination of volume "margin" normally required for low power and off ISO ambient operation where carbon monoxide (CO) compliance is most difficult to obtain. The stated goal was a BOZ volume reduction of 50% or greater while still meeting the typical performance requirements of the burnout zone.

Results

The concept ultimately developed for achieving the maximum size reduction resulted in a net BOZ volume reduction of approximately 39% relative to baseline Xonon technology. The achievable length reduction for a given volume reduction tends to be application specific and is dependant upon the geometry of the existing engine hardware in the region where Xonon interfaces with the engine. In the particular multi-can turbine platform CESI examined, the overall system length reduction based on the contribution from this individual task was 5.7 inches.

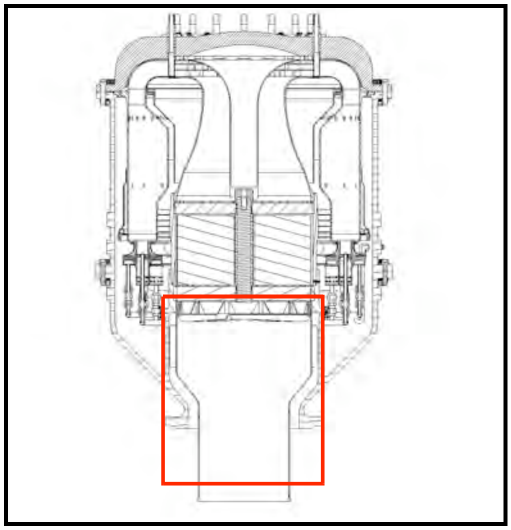


Figure 11 Cross section showing location of BOZ in the assembly

4.1.3.4. System Size Reduction Summary

To address the technical issue of size, several technology tasks were established all of which focused on size reducing key components. The components specifically targeted for size reduction included (1) the catalyst fuel-air premixer, (2) the catalyst section itself, and (3) the post catalytic combustion zone. All three technology tasks were successfully completed and resulted in length reductions of various magnitudes while required performance levels were maintained. Table 2 below describes the relative contribution of each component technology task to the overall Xonon system length reduction. Results are expressed on a percentage basis.

The total Xonon system length reduction attributable to the three aforementioned Multi-Can technology tasks is approximately 31%.

Technology Task	**Contribution to Overall System Length Reduction**
Reduced Length Premixer	8.5%
Single Stage "E" Class Catalyst	8.6%
BOZ Stabilization Devices	13.9%
Overall Xonon System Length Reduction	**31.0%**

Table 2 Xonon size reduction summary

The Figure 12 below shows a comparison between a Xonon system design based on existing technology compared to the equivalent design based on incorporation of Multi-Can technologies. The successful reduction in overall system size achieved under the Multi-Can program is evident from this visual comparison.

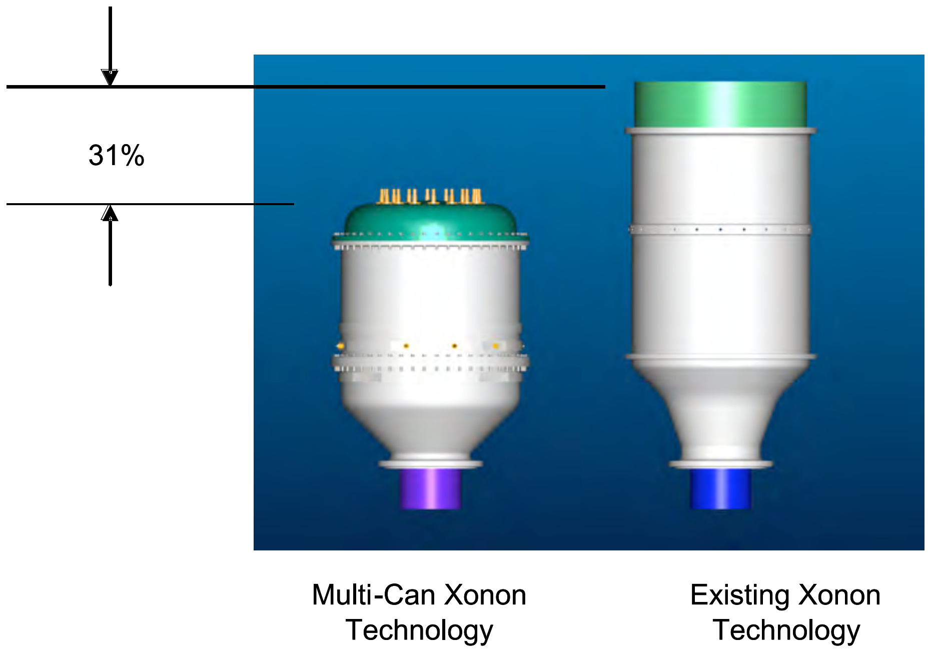
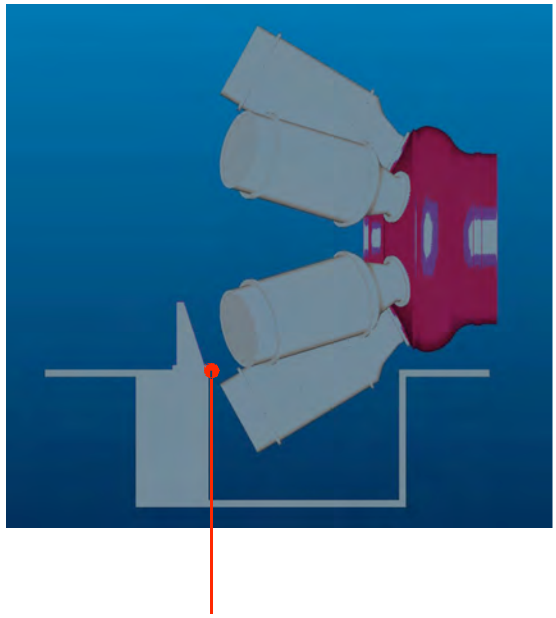


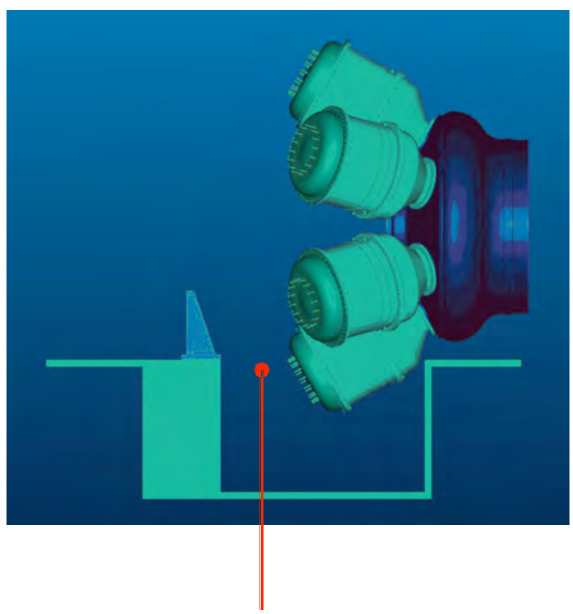
Figure 12 Xonon size reduction summary

Figures 13 and 14 below highlight the improvements in installation and removal clearances when multi-can technology is applied to a particular engine application. The depiction on the left shows installation of existing, conventional Xonon technology. The installation on the right shows the same engine application and the improved clearances visible when multi-can technology is applied.



3” clearance

Figure 13 Existing Xonon technology applied to engine application



14” clearance

Figure 14 Multi-Can Xonon technology applied to engine application

In terms of the size reduction objective, the Multi-Can technology validation phase resulted in a 31% overall length reduction for Xonon. Improvements in handling, installation and removal were made based on size reductions of three key components. The approaches in reducing the size of each component (mixer, catalyst and burnout zone) were validated through extensive reacting and non-reacting flow analysis, full pressure subscale rig testing and computational life modeling.

4.1.4. Performance

Several aspects of performance emerged as technical issues when conventional Xonon technology was applied to multi-can engine applications during the packaging studies. In particular, improvements in preburner temperature rise turndown capability as well as catalyst life and pressure drop are desirable as a means of improving the life and performance characteristics of the Xonon system as a whole. Technology tasks were implemented to address each of the aforementioned performance related issues. The technical issues, conceptual approaches for addressing the issues and the validation techniques adopted for confirming the validity of the approaches are all described in greater detail below.

4.1.4.1. High Turndown Preburner

Background

The conventional Xonon system utilizes a preburner upstream of the catalyst to facilitate engine startup, assist in load following and to compensate for catalyst aging. The preburner also provides the thermal energy required to elevate the compressor discharge temperature up to a level required for proper catalyst operation. The Figure 15 below shows the location of the preburner in a typical Xonon combustion system assembly.

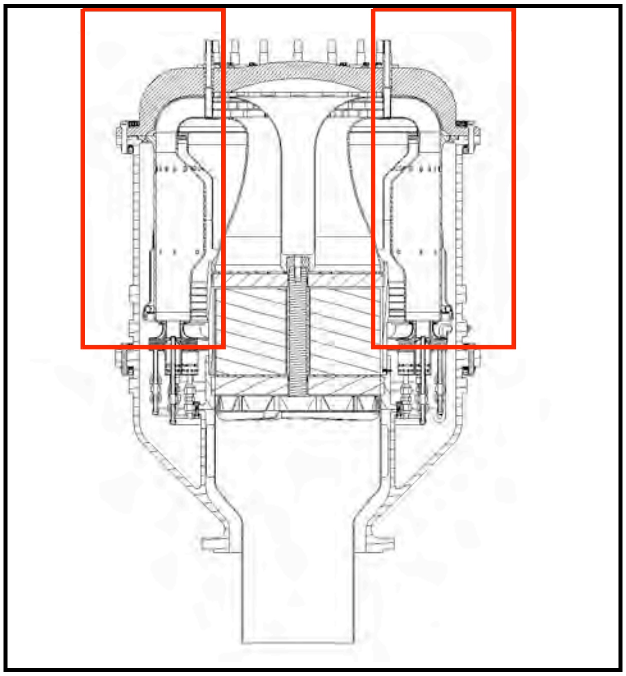


Figure 15 Cross section showing location of preburner in the assembly

The "existing technology" Xonon preburner is essentially a two stage, dry low NOx (DLN) combustor. The preburner demand ranges from very low thermal output (temperature rise) at full load on a high ambient temperature day to a very high thermal output at low power conditions on a low ambient temperature day. The ratio of the maximum to minimum thermal output is often referred to as "turndown ratio". The existing technology Xonon preburner has a useful temperature turndown capability of approximately 4:1. High pressure ratio engines, such as the multi-can machines identified and studied early in the program, feature high compressor pressure ratios and thus high compressor outlet temperatures. The preburner would therefore be required to potentially produce an extremely low thermal output at full load on a hot day. In one particular case, the minimum required temperature rise of the preburner under the extreme case was as low as 50ºF which requires a turndown ratio of 11:1. Thus, an improvement in preburner turndown capability was identified as a goal for multi-can applications.

Results

There are several means by which preburner turndown ratio can be improved. One approach for meeting these requirements is to incorporate an additional fuel stage sized to provide the very low (but stable) thermal output necessary at the very low, minimum temperature rise condition. The approach deemed most appropriate for addressing the technical issue of inadequate preburner turndown capability was to develop a preliminary design of a three stage, high turndown preburner which meets all of the performance requirements necessary for operation in high pressure ratio multi-can machines. The validation techniques employed for this task consisted of a mechanical design layout supplemented by detailed aerothermal analysis which supports the design. A cross section view showing the layout of the high turndown preburner is shown below as Figure 16. A 3D solid model depiction of the same layout is also included in Figure 17 for additional clarity.

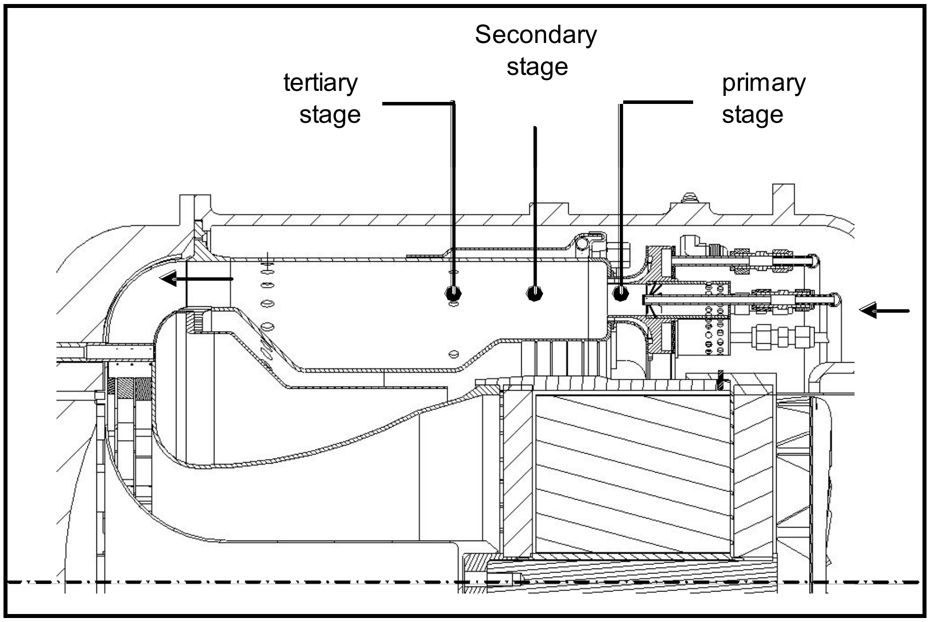


Figure 16 High turndown preburner cross section

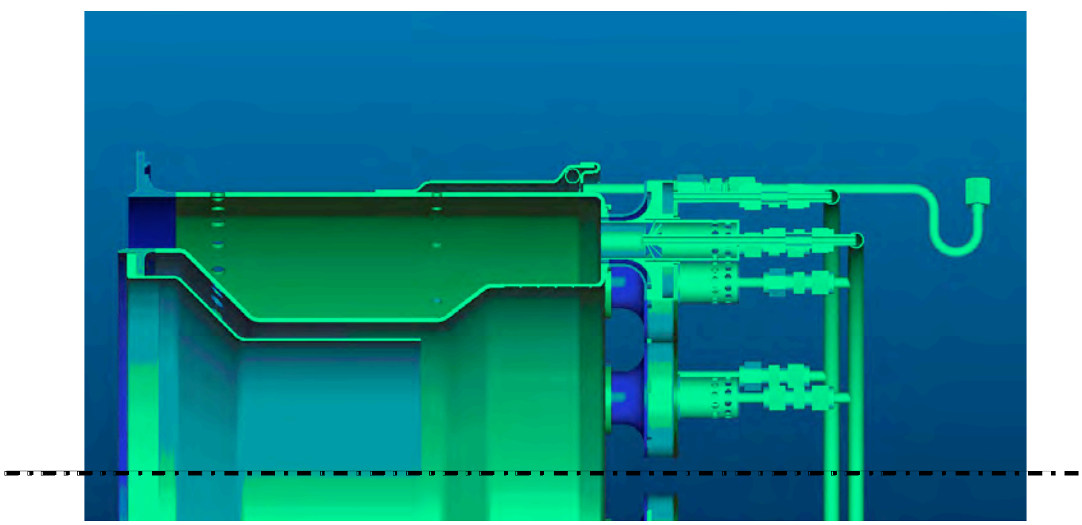


Figure 17 High turndown preburner solid model cross section

Detailed aerothermal analysis was performed to determine the airflow splits required to satisfy all performance requirements over the required load and ambient temperature range. Candidate fuel splits were also determined for both hot day and cold day conditions from 50 to 100% load. Representative engine exhaust NOx emissions were estimated based on an internally developed one-dimensional NOx model generated as part of this task. The model is empirically based and utilizes the following lean premixed NOx correlation as the basis for the preburner NOx predictions:

$$NOx_{(\text{ppm at }15\%\ O_2)} = 5.45\times10^{7}\ [1] \times\left(0.1P_{in}\right)^{(0.00221Tgas-4.0149)}\times e^{-28838/(Tgas+0.125[Tin-600])}$$

where: *Tgas* is bulk preburner gas temperature in deg K
Pin is inlet pressure of combustion air in atm
Tin is inlet air temperature in deg K

The NOx emissions specification for the multi-can application considered was NOx <2.5 ppm (corrected to 15% O_2) for the worst case condition. The highest NOx occurs at the 50% load point condition for a minimum ambient temperature day and with an aged catalyst. A plot of cold day exhaust NOx versus load for the cold day condition is shown in Figure 18. The NOx level can be maintained below the 2 ppm specification limit by appropriate allocation of air to all three zones of the combustor and achieving complete fuel-air premixing.

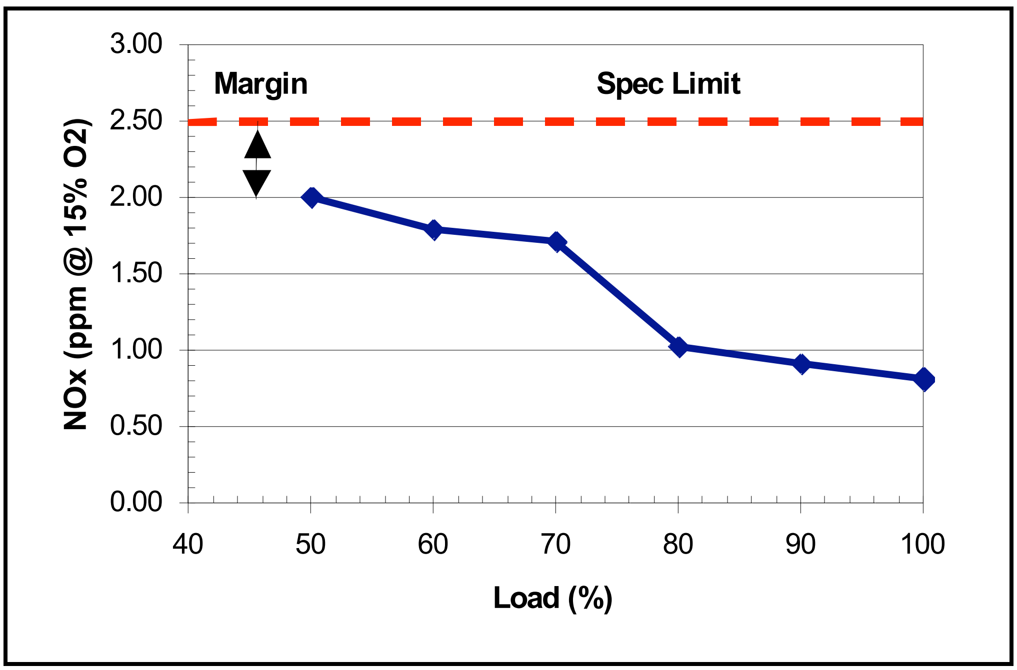


Figure 18 Cold ambient day engine exhaust NOx profile for high turndown preburner design

In conclusion, a preliminary mechanical design layout of an improved performance, high turndown ratio preburner with supporting detailed aerothermal analysis was developed. Although additional work would be required to optimize and verify performance prior to an actual engine

[1] Engineering Analysis for Lean Premixed Combustor Design, AIAA 95-3136, Magruder *et al.*, 1995.

application, the preliminary design of the high turndown preburner developed under the Multi-Can program is useful in bridging a key technology gap.

4.1.4.2. Catalyst Life Testing

Background

Improvements in single stage catalyst life potential and CESI's ability to more accurately predict catalyst life are two key technical objectives of the Multi-Can program. With that objective in mind, a task was initiated to collect kinetic and rate data for a variety of catalytic material formulations under various flow conditions and to examine their thermal stability. Thermal stability is important since a loss in catalytic activity narrows the operating window of the catalyst. Test data were gathered using several isothermal, high pressure, aging reactors (HPARs), such as that shown in Figure 19. Thus, the primary purpose of the test series was to better characterize the aging characteristics of existing and advanced materials under flow conditions simulating the combustion system environment over a broad range of humidity and temperature levels. Both catalytic powders and coated foils were tested. The data collected will also be useful as a basis for improving the "in house" predictive capability of the Catalyst Performance and Life Model (CPLM).

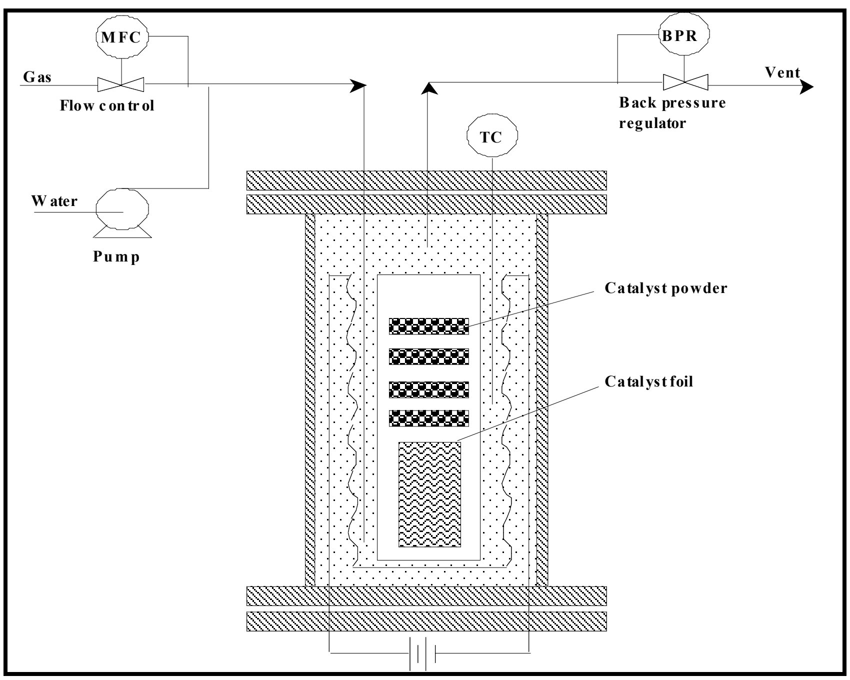


Figure 19 Cross section view showing internal detail of high pressure aging reactor

Results

In total, more than 2,300 run time hours were accumulated for various existing and advanced materials during the phase I portion of the program. A total of eight advanced material formulations were tested. Test results were useful in the determination of the kinetic rate constants related to coarsening, thermal aging the dependency of the rate laws and kinetics on water vapor concentration. Follow on activity will focus on gathering additional data and utilization of that data to improve our basic understanding of the life potential of these materials. Improvements to the catalyst performance and life model (CPLM) are planned.

4.1.4.3. Catalyst dP Optimization

Background

Improvements in system performance based on overall reductions in system pressure drop were identified as goals in the multi-can program. Reductions in parasitic pressure drop result in increased power output, reduced heat rate and lower fuel consumption. In particular, reductions in catalyst pressure drop and an assessment of how "optimized" the Xonon system is in that regard were identified as objectives under this task. To assess the pressure drop and transport characteristics of the baseline catalyst design as well as various advanced catalyst geometries under consideration, a test rig was devised and built to measure the heat transfer (i.e., mass transport rates) and pressure loss characteristics of a variety of catalytic foil corrugation patterns. In addition to this activity, a literature search was conducted to supplement and improve our overall understanding with respect to pressure drop and mass transport for channel flow in geometries of this type.

Results

A schematic of the test rig is shown as Figures 20 and 21 below. The operation of the test rig will not be described in detail in this report. However a brief description of the rig follows. Through the use of the principal of dynamic similarity, a pair of flat plates was manufactured with the proper corrugation pattern machined into the surface at twice (2X) scale relative to an actual Xonon catalyst module. The bottom copper plate (see fig 16 below) is heated with a hot water source and the top Plexiglas plate is not heated. Cold water flows through the channel established by the plate pair and heat transfer (i.e. mass transport) occurs between the hot bottom plate and the cool water flowing through the corrugated channel. The cold water is intended to simulate the gas flow in the corrugated, coated channel in an actual catalytic application. Dynamic pressure losses are measured along the length of the channel from high to low pressure using digital manometers.

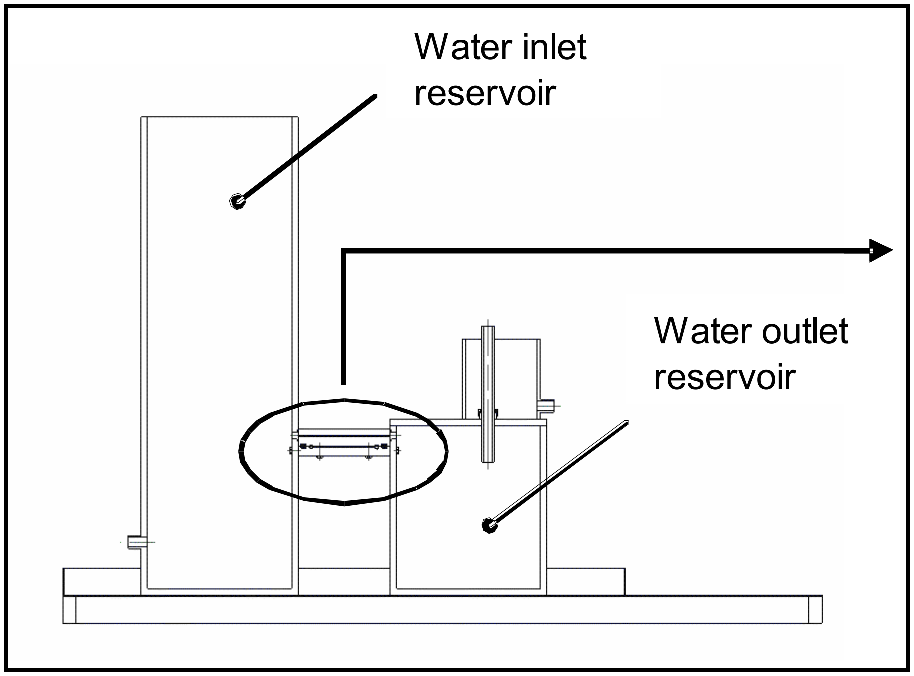


Figure 20 Schematic view of water flow test rig – the rig is useful in measuring catalyst pressure loss and transport characteristics

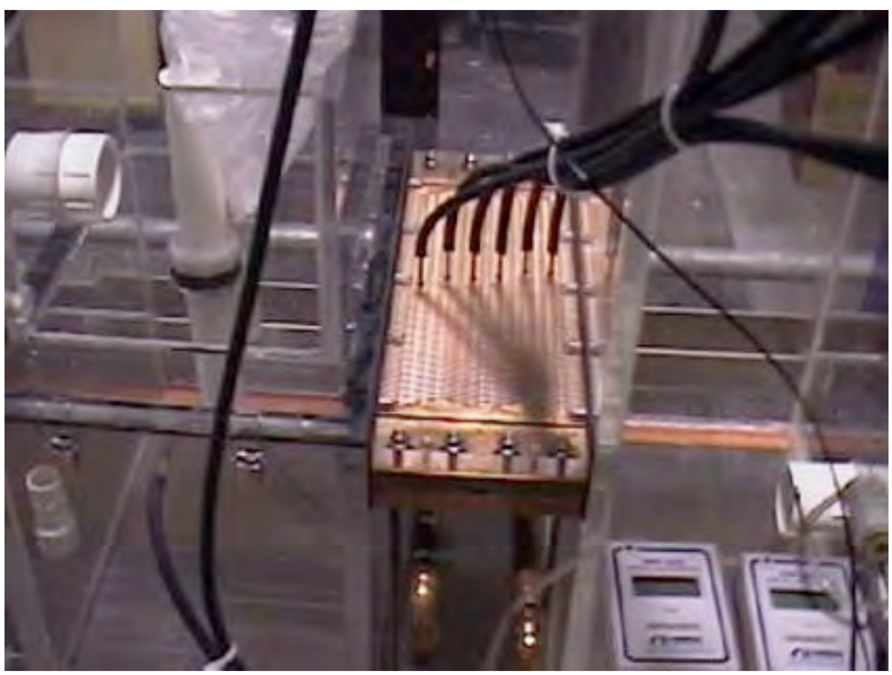


Figure 21 Photograph showing typical test section with applied instrumentation

Typical data gathered from the water flow rig is shown in Figure 22 for a particular plate set combination. The trends show the increase in overall mass transport (through the heat-mass transfer analogy) with increasing channel Reynolds number. Figure 23 shows the reduction in effective, overall friction factor with increasing Reynolds number. The plot follows established trends consistent with the Moody Diagram.

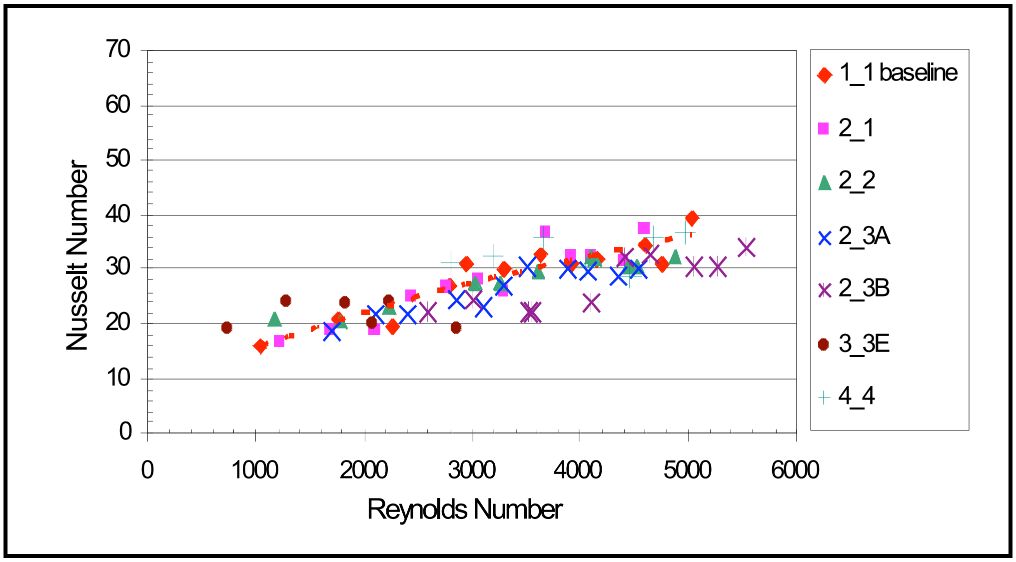


Figure 22 Nusselt number vs. Reynolds number for various plate combinations

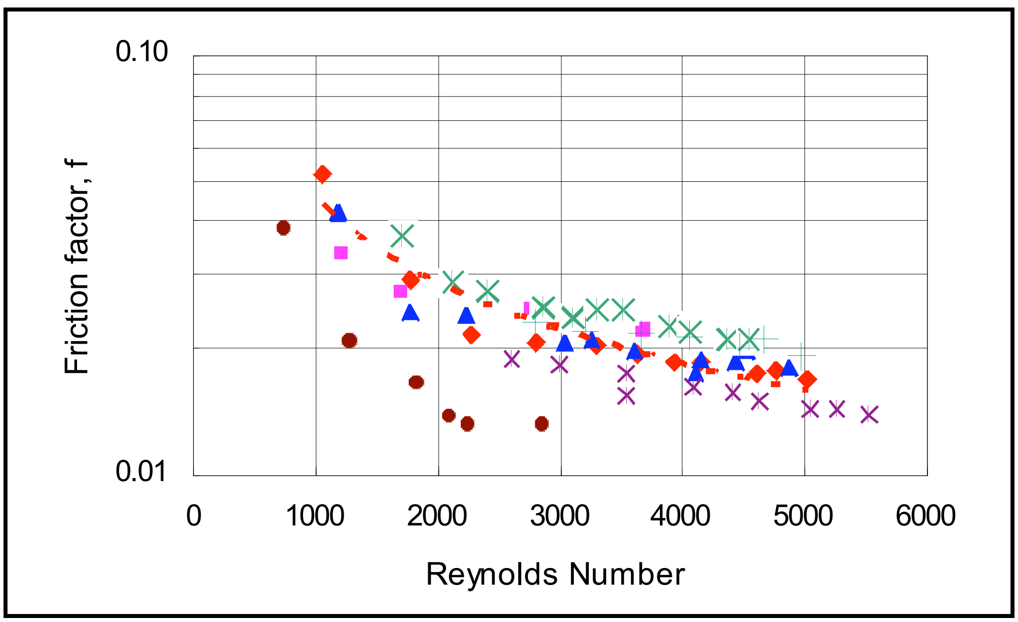


Figure 23 Friction factor vs. Reynolds number for various plate combinations

4.1.4.4. Performance Summary

To address the issue of performance, several technology tasks were established to improve the overall performance and life capabilities of two particular Xonon components. The components which have been improved include the preburner and the catalyst.

Detailed aerothermal analysis indicates that Xonon preburner turndown capability has been improved under the Multi-Can program. The improvement was accomplished through the addition of a third pilot fuel stage sized to produce the very low temperature rise at the "worst case" condition. Through the addition of the extra stage, the calculated turndown capability of the preburner has been improved from 4:1 to nearly 11:1. Optimization of the airflow distribution necessary to ensure rapid transient response and load following capability was also accomplished as part of the task.

An improved understanding of the life potential, aging characteristics and pressure loss characteristics of the Xonon catalyst was obtained through successful completion of two catalyst related technology tasks. They were entitled "Catalyst Life Testing" and "Catalyst dP Optimization". The catalyst life testing task resulted in the acquisition of important data for improved insight into the sintering, kinetics and rate properties of several existing and advanced single stage catalyst material formulations. The catalyst dP optimization task was useful in guiding our understanding of the various contributors to the overall pressure loss for the flow through a catalyst.

4.1.5. Controls

Controls related challenges were identified as potential technical issues in the application of Xonon to multi-can machines. In particular, simplifications to CESI's current model based controls approach were identified as important in applying Xonon in a cost effective manner to multi-can machines. Simplifications in the form of reduced instrumentation count, more robust and simpler feedback and simplified means of compensating for catalyst aging were all examined. Thus, two technology tasks were implemented and successfully completed under the multi-can program. They were:

Fixed Fuel Split Based Controls – This task evaluated the feasibility of controlling the Xonon combustion system by controlling fuel flow to each zone to a fixed split ratio based on some fundamental engine parameter. The split ratios would be established for both the acceleration and loading portion of the engine duty cycle and compensation for variations in ambient temperature would be required. This approach is commonly used by various gas turbine OEMs.

Sensor Based Feedback – This task was useful in identifying various means of using continuous and discrete feedback from sensors located throughout the system to compensate for the effects of catalyst aging.

Thus, two control system related tasks were established and successfully completed and both proved helpful toward (1) identifying simplifications to the basic Xonon combustion system controls approach for multi-can applications and (2) identifying practical means of compensating, at the system level, for the effects of catalyst aging.

4.1.5.1. Fixed Fuel Split Based Controls

Background

A "fixed fuel split" based controls approach is commonly used by various gas turbine OEM's for combustion system control. The philosophy behind the approach is that predictable combustion system operation is possible in a simplified manner by establishing fixed fuel splits to each leg of the system over the acceleration and engine loading range. The values are established early in the combustion system development cycle. The splits are then tuned and optimized as part of the normal site commissioning process. The fixed fuel splits would be referenced to some measurable engine fundamental such as rotor speed, exhaust gas temperature (EGT) or delta EGT (load). The approach represents progress towards simplifying the Xonon controls approach due to the elimination of feedback instrumentation and associated complex model-based logic.

Results

An evaluation of the feasibility of applying a fixed fuel split based control approach in a Xonon type multi-can application involved sensitivity analysis of both the acceleration and loading portions of the duty cycle. Existing engine data from the single can Xonon machine currently in operation (KHI M1A-13X at Silicon Valley Power) was used to evaluate existing operating trends in terms of the variation in preburner outlet temperature spread and NOx emissions spread over the duty cycle range. These existing trends then formed a basis of comparison to calculated changes in variations when a fixed fuel split based controls approach is implemented. NOx emissions during the loading portion of the duty cycle were determined to be an important part of the sensitivity analysis since the fixed fuel split based approach would result in the elimination of the existing array of gas temperature thermocouples (and the associated feedback and control they provide) at the outlet of the preburner. The other important part of the analysis was an evaluation of the potential impact of increased preburner outlet gas temperature spread on the operating window of the catalyst.

Based on the analysis, it was determined that a fixed fuel split based control approach is very feasible for the acceleration portion of the engine duty cycle irrespective of the normal variation in ambient temperature. Instrumentation used in our current application for feedback and trim control would be eliminated if the fixed fuel split control approach is implemented. Further, it was determined that fixed fuel split control is feasible for the loading portion of the duty cycle for an ISO ambient day. The feasibility of this approach for off-ISO ambient conditions requires further evaluation. The impact of potential increases in preburner outlet temperature spread which may accompany the elimination of preburner discharge gas thermocouples would also require further evaluation and may reduce the size of the catalyst operating window. Evaluation of this effect and its magnitude is likely to be platform specific.

To summarize, implementation of a simplified, fixed fuel split based controls approach has potential feasibility in the application of Xonon to multi-can machines. Further work is required to assess the impact of this combustor control approach on the NOx emissions and catalyst operating window.

4.1.5.2. Sensor Based Feedback and Control

Background

With most or all catalytic combustion systems, thermal aging is a normal consequence of catalytic material exposure to elevated gas temperatures for extended periods of time. The effects of thermal aging typically show up as a gradual reduction in system performance. This often manifests itself in terms of increased carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions measured in the engine exhaust. The CO and/or UHC emissions typically begin to creep higher due to the gradual movement of the burnout zone combustion wave front further aft (closer to the turbine inlet) which reduces the time available for CO and UHC oxidation. A compensation approach utilizing a control strategy which automatically adjusts some key engine parameter, in either a discrete or continuous manner, is considered useful in the successful multi-can field deployment of Xonon.

With that objective in mind, a task was initiated early in the multi-can program to develop and qualitatively evaluate a series of control strategies which could be applied to Xonon equipped machines for the purposes of compensating for catalytic aging.

Results

Several controls approaches for catalyst aging compensation were identified and evaluated during the Multi-Can Technology Validation phase. Level IV logic diagrams were developed and documented for each of the approaches developed. The logic diagrams are useful in documenting the approach for future implementation and also shortening the implementation time if the control strategy were adopted and applied to an actual multi-can engine.

All of the approaches rely on the measurement of some fundamental combustion system or engine exhaust parameter using sensors to detect degradation in catalyst performance. If system degradation is detected, appropriate trim signals are generated and corrective action is taken. This adjustment may come in the form of adjustments in either (1) the thermal preheat supplied to the catalyst or (2) the catalyst equivalence ratio. The former can be modified by adjusting the fuel splits to the preburner and the latter can be accomplished through an adjustment to the bypass valve setting or some other air management system. Multiple UV sensors located on the burnout zone which detect the location of the combustion wave front are proposed as another means of controlling emissions by providing positive locating ability of the combustion wave. Through robust and predictable location of the combustion wave front, engine exhaust emissions can be controlled to guaranteed levels as the catalyst ages.

Risk analysis of the various strategies highlighted typical concerns. In particular, the robustness, potential drift, cost and reliability of the instrumentation with each approach are issues requiring additional scrutiny if they are implemented. The UV sensor approach in particular has associated risk due to issues related to optical line of sight, optical cleanliness requirements in an actual "on engine" application and potential hysteresis effects.

In summary, CESI has identified various technical approaches for compensating for catalyst aging in the application of Xonon to multi-can machines. The optimal approach is application specific and additional work is required in the application phase to further evaluate and customize the preferred approach.

4.2. Incorporation of Advanced Catalyst Material Manufacturing Processes into the Catalyst Module Design

4.2.1. Introduction

The principal objective of this task was to develop and incorporate advanced catalyst material manufacturing methods to improve the economics of catalyst module manufacturing.

4.2.2. Approach

The following steps were used to (1) develop an advanced catalyst material manufacturing process for use in catalyst module inlet stages and validate the material performance using CESI's catalyst test facility, (2) scale up the advanced manufacturing process to meet commercial lot size requirements which includes optimization and characterization of process parameters for both the inlet stage material as well as the previously developed outlet stage material, specification of capital equipments, and subscale high pressure reactor (HPR) validation testing, (3) optimize the catalyst design configuration based on the material performance characteristics consistent with the advanced manufacturing process focusing on design features and performance parameters which can be deployed to all Xonon applications, and (4) manufacture and conduct engine (KHI-M1A-13X) test of a full scale catalyst module at CESI's Silicon Valley Power facility to validate the material/system performance for 1500 hours followed by a teardown/inspection of the test module.

4.2.3. Results

4.2.3.1. <u>Advanced Inlet Stage Catalyst Material Manufacturing Process</u>

CESI developed an advanced inlet stage catalyst material process. It is a new formulation and method that has advantages that include reduced variability with overall safer and simpler processing.

Subscale validation testing of new inlet material on an existing design shows that it has similar performance activity at higher catalyst inlet temperatures as the current inlet stage material. Unfortunately, at lower inlet conditions it appears to have a rapid drop off in performance. Figure 24 shows a graph of inlet stage performance versus catalyst inlet condition. The two sets of data in the graph are a comparison of the new inlet and the current inlet materials. The new inlet material differs only by 0.5% to the current material. The performance drop at lower inlet conditions is confirmed with a catalyst light off test, a test which determines the required temperature for the catalyst to remain lit and stable. The new inlet material light off requirement is 9% higher than the current materials. Although this increase in required inlet temperature minimally impacts performance for the Kawasaki M1A-13X gas turbine, it is unfavorable in its current formulation to be applied throughout the Xonon product line. It is for this reason that the new inlet material was not incorporated into the redesign and engine validation test.

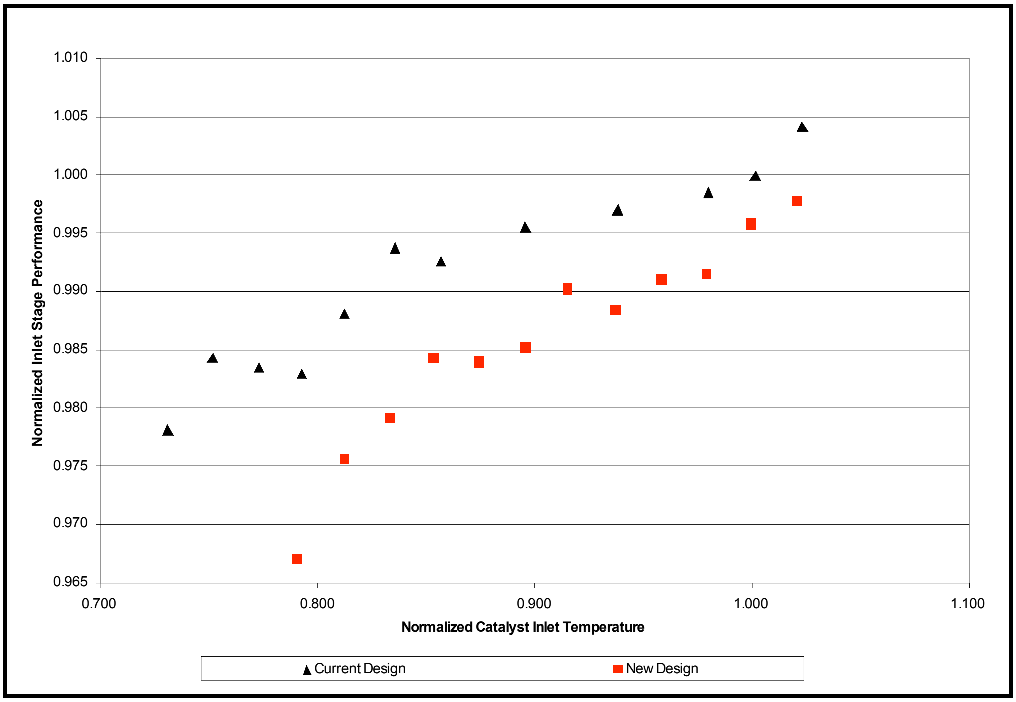


Figure 24 New vs. current inlet stage performance

4.2.3.2. <u>Scale Up of Advanced Manufacturing Process to meet commercial size requirements</u>

To meet commercial lot size requirements, CESI scaled up an advanced manufacturing process with the addition of a second coating line, CL2. A variety of factors were characterized and optimized. Among the improvements and benefits of CL2 over CL1 are axial coating distribution uniformity, increased coating capture efficiency, more automation, and capability for increased production capacity by a factor of two. Catalyst foils manufactured on CL2 are consistent in thickness of loading and performance with those made on CL1. Figure 25 shows a comparison of loading samples by CL1 and CL2. The CL2 samples are very close to the mean and well within the range of the upper control limit (UCL) and lower control limit (LCL) of CL1 samples. Lot-to-lot variability is small with CL2. Figure 26 shows a graph of catalyst outlet stage performance versus catalyst inlet conditions (mainly temperature). The plot has data from two lots that were tested twice each. The close grouping of all the data shows that there is very small lot-to-lot variability (~0.5%) and test repeatability (~0.5%).

The current outlet stage material availability is limited by its complexity and labor intensiveness for manufacturing in large quantities. The scaled up advanced outlet stage material was developed in tandem with the development of CL2 to address this concern. The material has the benefits of improved adhesion/cohesion and reduced variability.

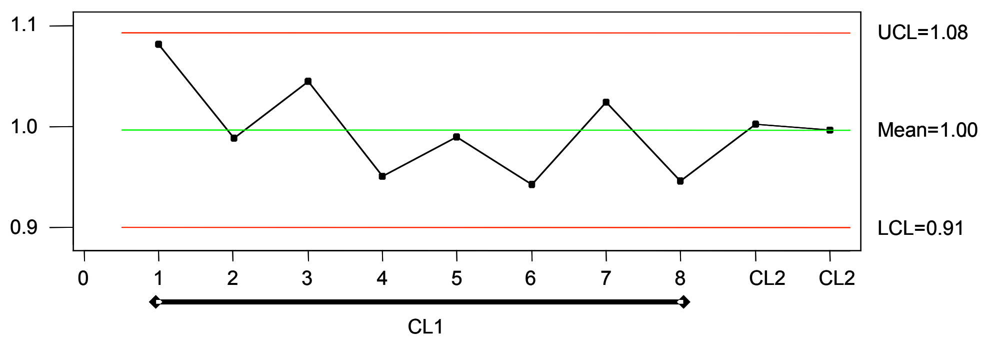


Figure 25 CL2 and CL1 loading comparison

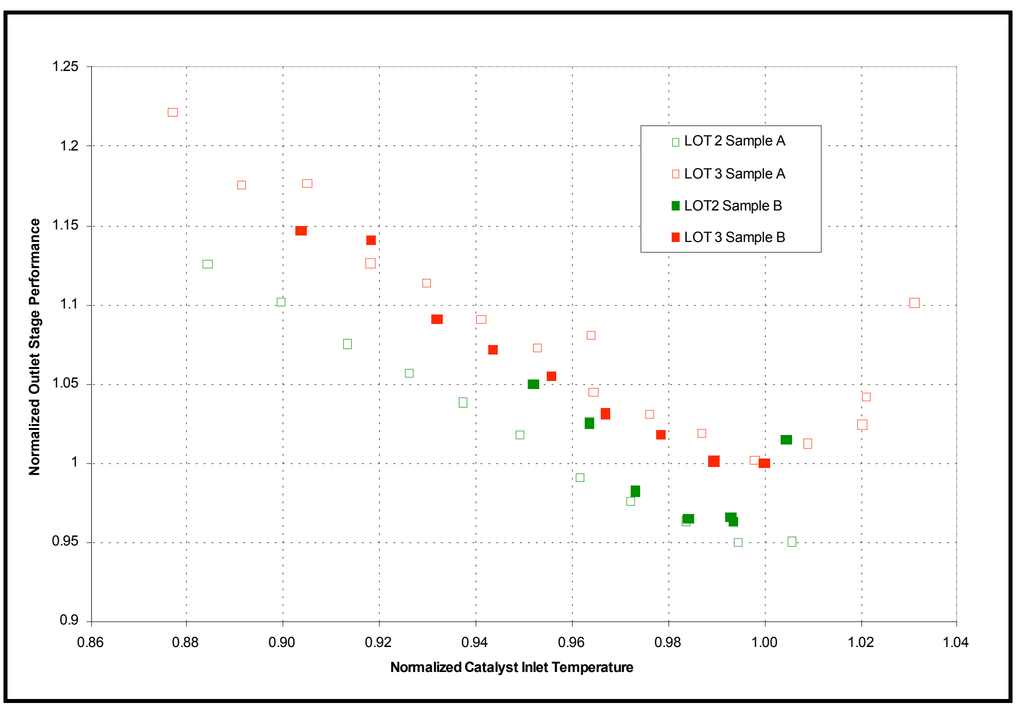


Figure 26 CL2 Lot-to-Lot variability

4.2.3.3. Optimization of catalyst design configuration based on material performance of advanced manufacturing process

The new outlet stage material, which is a scaled up version of the current outlet stage material, was applied in a catalyst system redesign effort. The catalyst system consists of an inlet stage and outlet stage. The redesign takes advantage of a more balanced fuel conversion between the inlet and outlet stages, i.e. each stage combusts the same amount of fuel. The extent of combustion of fuel through the catalyst is referred to as conversion. It is typically calculated by taking the temperature rise across the catalyst (temperature at outlet of catalyst minus temperature at inlet of catalyst) and dividing it by the maximum possible temperature rise assuming conversion of all the fuel to heat. This balanced approach allows the catalyst to age more slowly and extend operating life. Subscale high-pressure rig testing results were generated for each design phase (Preliminary, Detailed, and Verification). Each phase was subject to a design review where it had to fulfill specific internal CESI requirements.

Verification Phase results were acceptable. The inlet stage catalyst light off requirement was 6% higher than the current design but well below the operating range of the engine. Figure 27 is a graph of catalyst inlet stage performance versus catalyst inlet condition (mainly temperature) and shows where the catalyst transitions from being unlit to where it lights off and becomes stable.

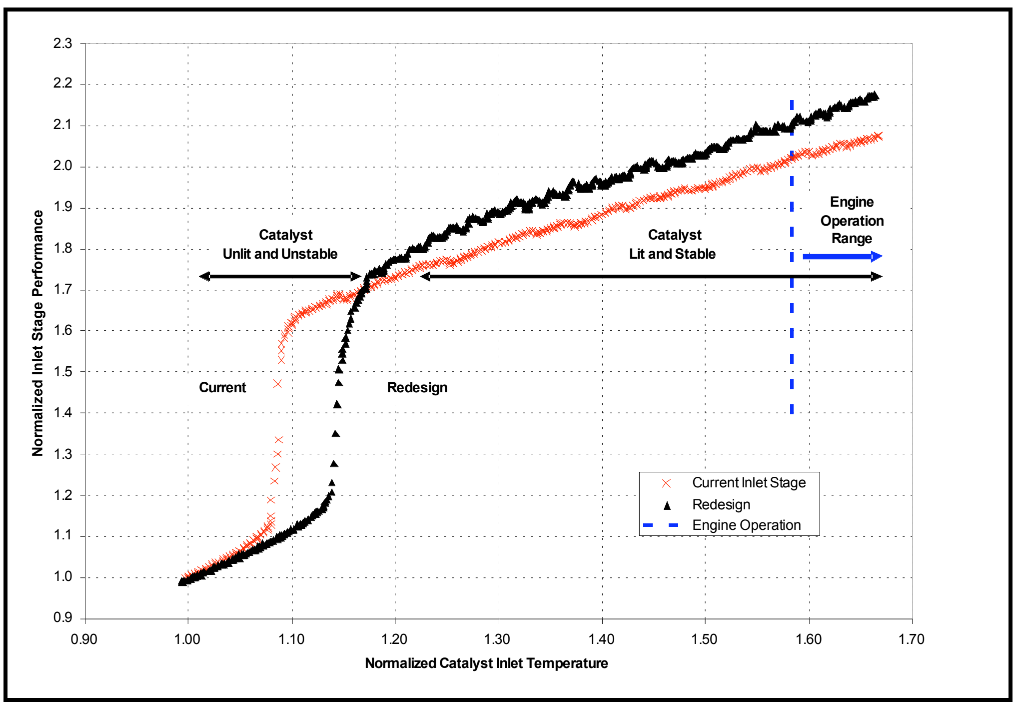


Figure 27 Redesign inlet stage light off requirement

The catalyst system performance, or conversion, for the Verification Phase was acceptable. Figure 28 shows the system conversion versus catalyst inlet condition. The two sets of data represent the two samples tested. Furthermore, the catalyst performances of the outlet stage and the inlet stage, when tested individually, were within the performance targets. The results for the outlet stage are shown in Figures 29, and for the inlet stage in Figure 30.

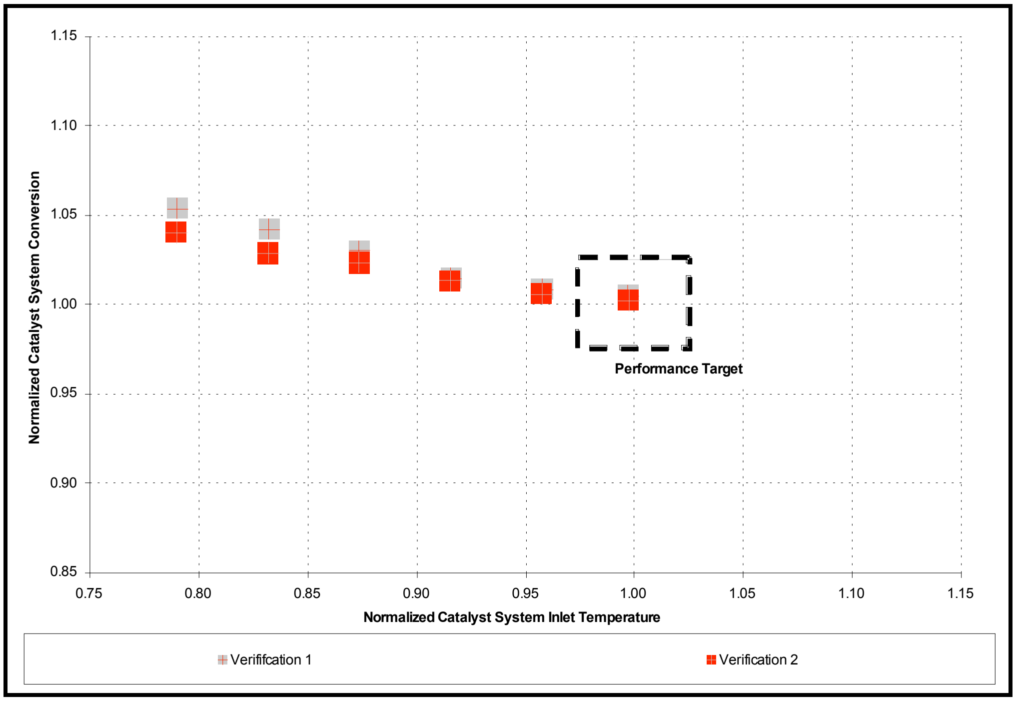


Figure 28 Catalyst system performance

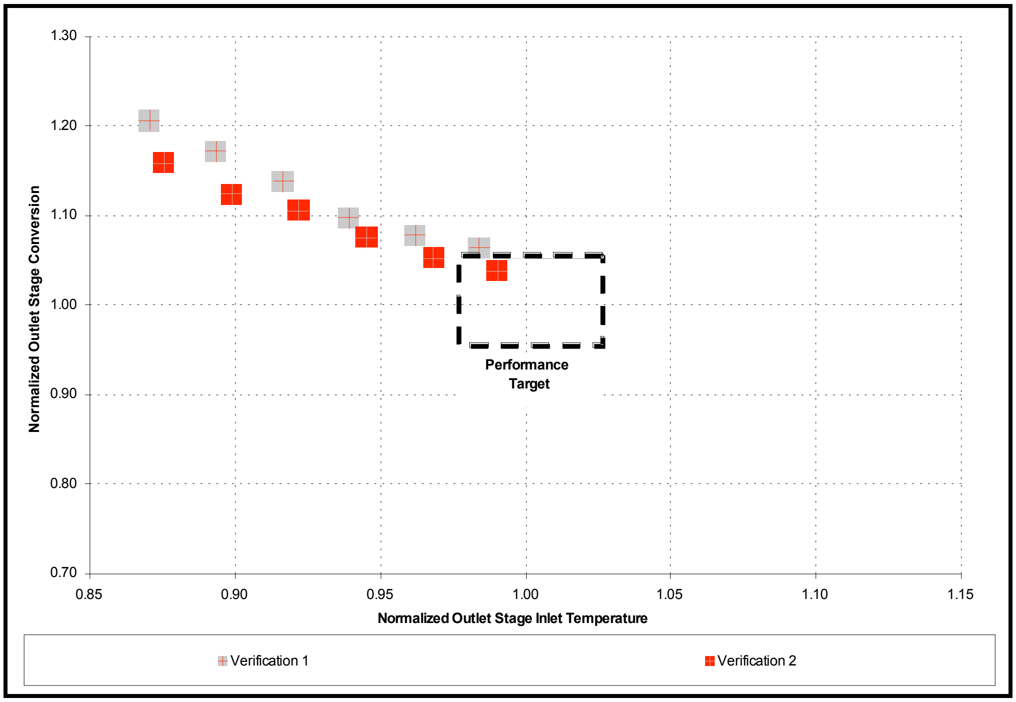


Figure 29 Catalyst outlet stage performance

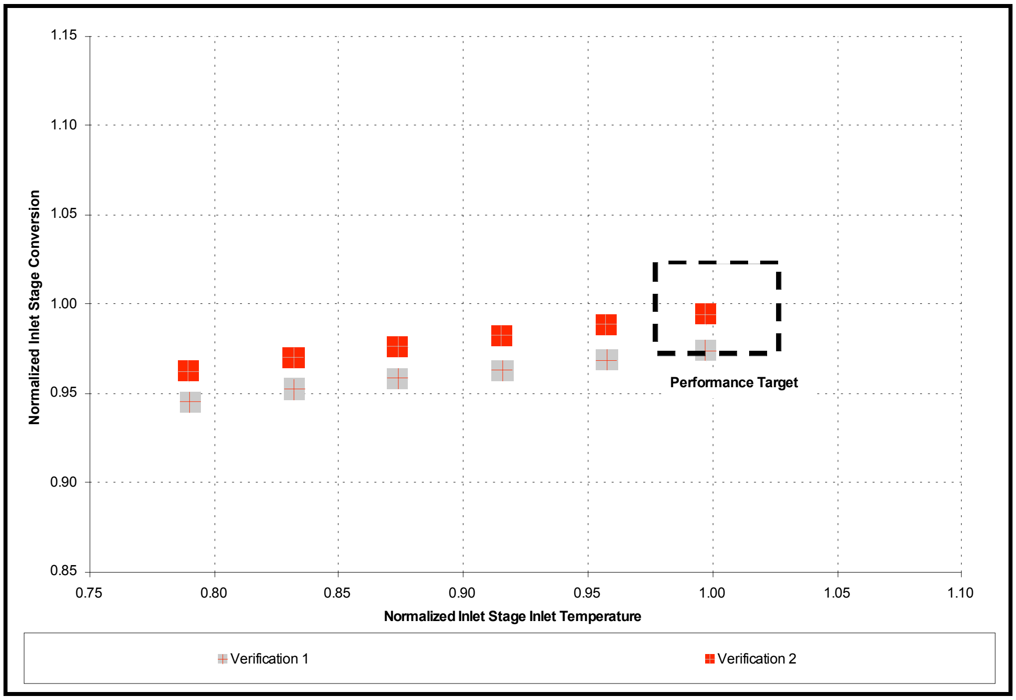


Figure 30 Catalyst inlet stage performance

4.2.3.4. Manufacture and conduct engine test of full-scale catalyst module

A full-scale module incorporating the redesign was manufactured on the new coating line. It was engine tested at CESI's Silicon Valley Power facility. It commenced on April 15, 2004 and ended on June 4, 2004. During that unattended (24hr/day 7days/week) operation, it completed 1200 hours of operation while emitting emissions levels of less than 2 ppm NOx, less than 10 ppm of UHC, and less than 10 ppm of CO. The reduction in operational hours from originally targeted 1500 hours was deemed acceptable. Completing the additional 300 hours was unnecessary because the 1200 hours of data gathered already showed a lined-out flat conversion profile used to assess and validate the material performance (see Figure 32).

Other tests included in the run were bi-weekly load maps. These were performed to verify and ensure load turndown capabilities. Figure 31 shows a graph of CO concentration versus load during one of the load map tests. The turndown capabilities were very good; CO was well below 10 ppm down to 60% load. CESI's current commercial guarantee for load turn down is CO levels less than 10 ppm down to 70% load. The catalyst system performance was as expected and inline with CESI's Catalyst Performance Life Model (CPLM). Figure 32 shows this in a graph of system conversion versus operational run time where the data trends with the model line beginning at the 300 hour mark. Since the model requires a minimum number of data points to estimate wall temperature profiles, it was unable to accurately predict performance during the first 300 hours of the validation test. The model only receives operating and boundary condition changes every few hundred hours which helps explain the divergence between the model and the engine results. Each data point reflected in Figure 31 is a thirty minute average of six points taken every five minutes.

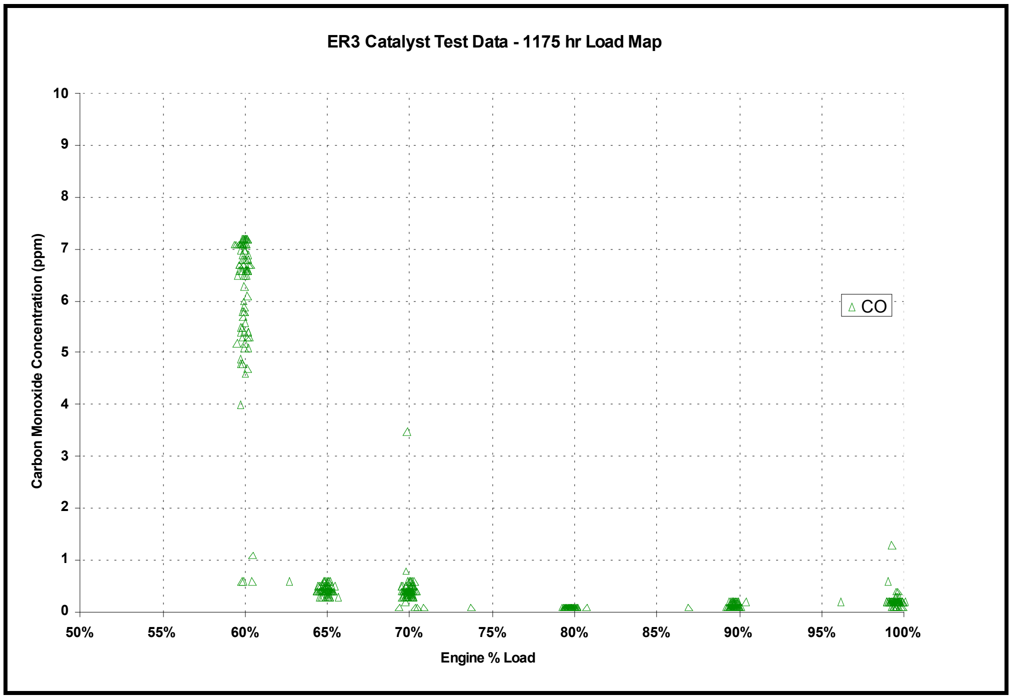


Figure 31 Emissions at part load

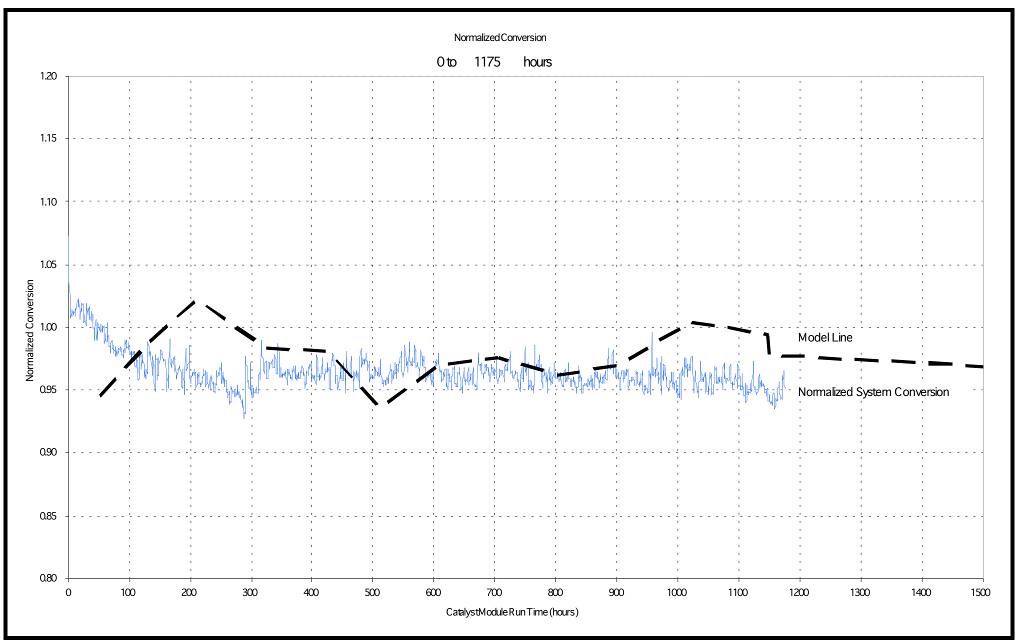


Figure 32 Catalyst performance

Subsequent teardown and inspection of the module revealed no anomalies.

4.2.4. Conclusions

The catalyst design configuration was modified to allow for a better distribution of temperature rise through the catalyst that would contribute to increased component life.

CESI successfully scaled up the manufacturing process for the previously developed outlet stage catalyst material. The redesigned catalyst module incorporating the advanced scaled up outlet stage material was tested in both subscale and full scale engine testing. The engine testing showed that the scaled up outlet stage material has better performance characteristics than the currently used material.

Unfortunately, the scaled up process for the inlet stage materials yielded catalyst material with a higher light off requirement that did not meet performance requirements and therefore was not incorporated into the tested configuration. Further development of the inlet stage material will be required before introduction into the product line.

The manufacturing process improvements conducted throughout this task provide CESI the opportunity to more efficiently produce catalyst modules.

4.3. Manufacturing Process Quality Improvement

4.3.1. Introduction

This section describes work completed to improve the overall quality of the catalyst module manufacturing process. The goals of this task were to:

Understand the manufacturing variation associated with the production of Xonon products.

Initiate improvement efforts for the related manufacturing processes.

4.3.2. Approach

Use the tools of Six-Sigma to Define, Measure, Analyze, Improve and Control the manufacturing processes used in producing Xonon products, to achieve a stable and capable manufacturing process.

4.3.3. Results

The results are presented in the context of the Six-Sigma process, Define through Control.

4.3.3.1. Define

The goal of the Define phase is to comprehensively document the processes for evaluation, ensuring the current state was well understood. Catalyst Manufacturing was divided into several unique steps (see Figure 33). Each unique step was evaluated by process owners and support personnel with the output being a process map with a comprehensive list of process inputs and outputs, list of the measured attributes and clear understanding of gaps between expected and actual performance. Several initial improvements were made, most aimed at ensuring manufacturing techniques are performed consistently as intended.

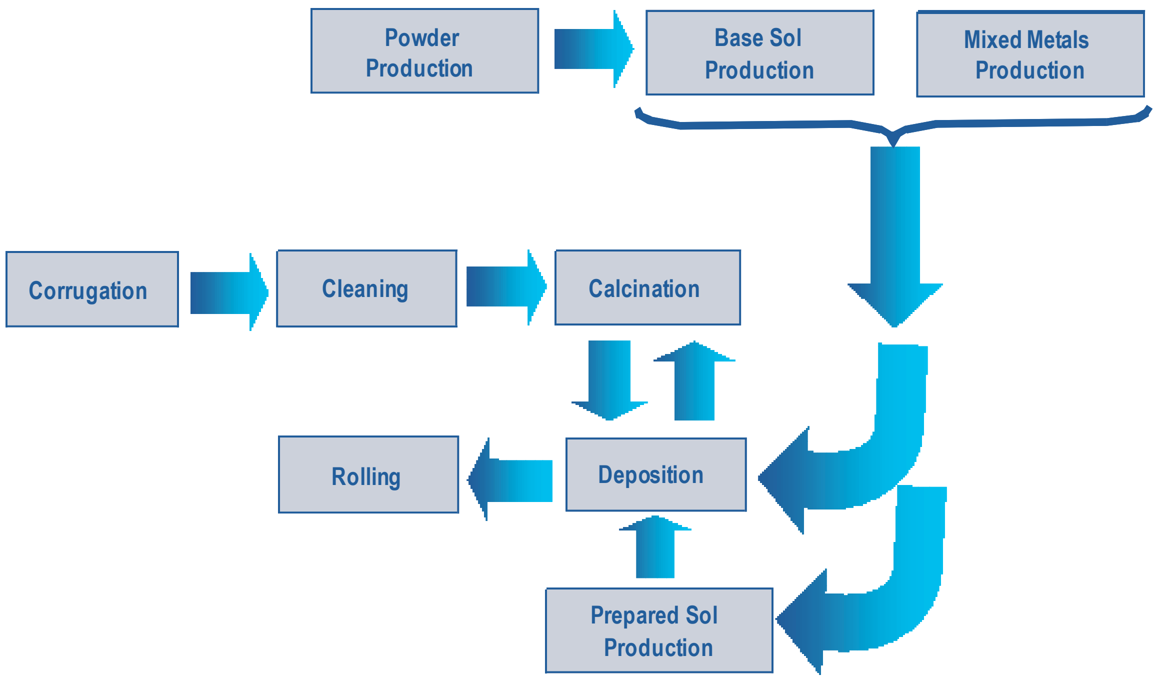


Figure 33 Catalyst manufacturing steps

4.3.3.2. Measure

The goal of the Measure phase is to ensure key measurement systems are adequate to assess manufacturing process variability. The main function of manufactured catalysts is to provide the specified temperature rise when operated at a set of defined conditions. Therefore, the key measurement systems to evaluate are the systems associated with measuring the temperature rise of manufactured catalysts along with the systems used to assess key in-process and post-process variables. The temperature rise measurement system is the High Pressure Rig (HPR).

Measurement system evaluations were performed on the HPR and other key systems. As the HPR test operation is not completely automated and various test hardware is utilized, several variables were introduced to ensure a complete view of the variability was captured. A three factor, two level designed experiment was performed. The factors were:

- Catalyst section (assess differences in insulation and instrumentation)
- Catalyst roller (assess differences in tension and instrumentation)
- HPR operator (assess difference in rig operation)

Four repeat points were added to obtain a total of 12 experiments. Catalytic foil from a recently produced product was utilized for the experiment. As the test is destructive in nature, the source foil was assumed to be completely uniform.

Thorough analysis of the experimental results indicated an overall process standard deviation of 1.5 units with respect to a performance specification spread of 1.8 units. The test instrumentation was immediately found to be inadequate. Thermocouples inserted at theoretically the same location within the test system (e.g., outlet gas) sometimes varied over a range four times greater than expected.

The resulting experimental model did not produce a good fit (low R squared value). However, catalyst section and catalyst roller did appear to have a significant effect (see Table 3, P-value of 0.06 equates to a 6% probability of getting the result by chance).

R squared	0.4907
	P-value
Section	0.0616
Roller	0.0731
Operator	0.3195

Table 3 HPR experimental results

Various additional attributes were assessed to further understand the measurement system variability. These included pressure drop, weight and foil orientation. Correlation plots for both pressure drop and weight trend with temperature rise, indicating again the rolling of the test sample is a significant factor.

Other key measurement systems were analyzed in a similar fashion. A variety of improvement opportunities were noted and acted upon. Improvements to the HPR system included the addition of thermocouples, improvement of data collection software, inspection and repair of test section insulation and modification of rolling techniques. The resulting variation in the various measurement systems were deemed from marginally adequate to highly adequate.

4.3.3.3. Analyze

The goal of the Analyze phase is to quantify the process variability inherent in the overall manufacturing process. To accomplish the goal, a typical catalyst product design was chosen and independent samples were made every other week over a three month period. Although not the preferred sample size to quantify the process variability with great precision, the time and cost associated with producing a large quantity of samples prohibits a larger sample size. The improved HPR was utilized to gather performance data. To assess the HPR improvement, two data points were gathered for each independent sample produced. Hence, the variability within a subgroup is an additional estimate of the measurement system variability, and the variability between subgroups is an estimate of the manufacturing process variability (see Figure 34).

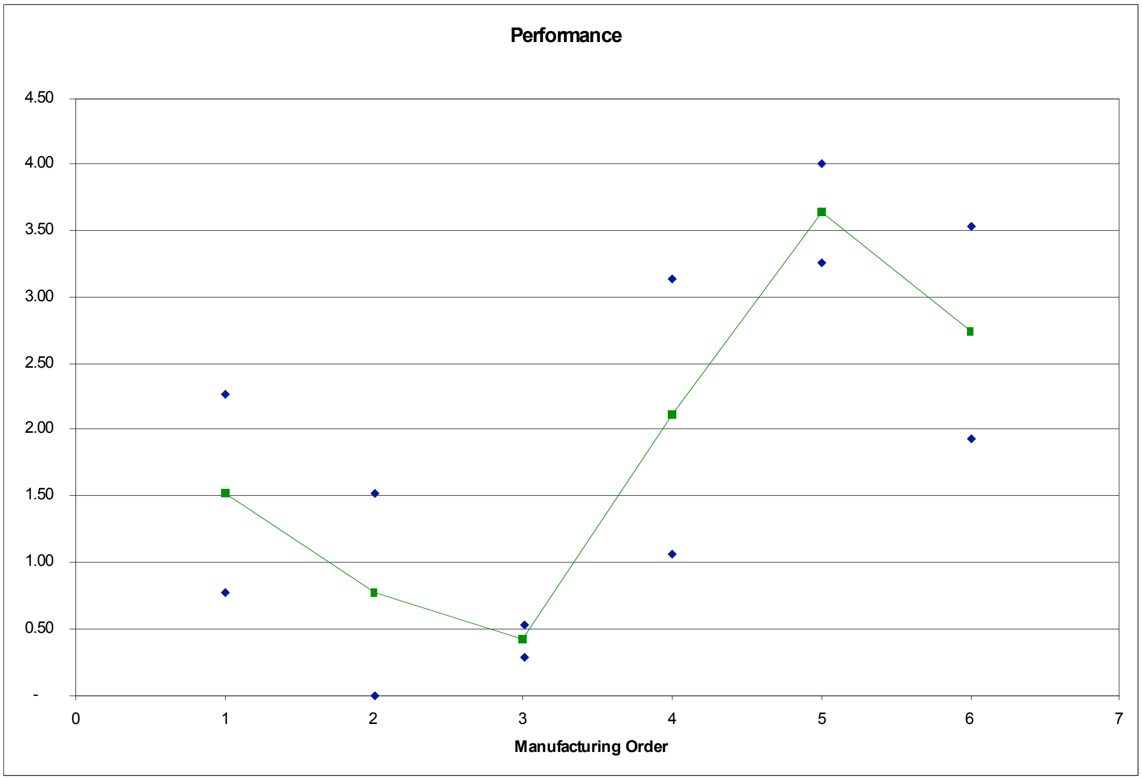


Figure 34 System conversion (normalized) in the order manufactured

The standard deviation of the manufacturing process was calculated at 0.7 units (note: units in the above Figure 4.3.3 are not the same units as the standard deviation due to data confidentiality) and the standard deviation of the measurement system was calculated at 0.9 units. Thus, the combined variability was 1.1 based on adding the individual variances. To achieve the overall program goal of a capable manufacturing process, the process potential (C_p) must be at least 1.0.

$$C_p := \frac{\text{SpecificationSpread}}{6 \cdot \sigma}$$

Based on the variability estimated and typical design specifications, the process potential was estimated at 0.5, well below the goal. Assuming a process centered between the specification limits, the current product yield was estimated at 89%, realizing any shift in the process will greatly affect the yield.

Initial improvements to process potential were gained by increasing the number of tests run and utilizing the average value to assess performance.

$$\sigma_{improved} := \frac{\sigma_{original}}{\sqrt{SampleSize}}$$

Four tests were chosen, which reduces the standard deviation associated with the measurement system from 0.9 to 0.4 and the overall process standard deviation from 1.1 to 0.8. The corresponding yield improves from 89% to 97% for a centered process (see Figure 35).

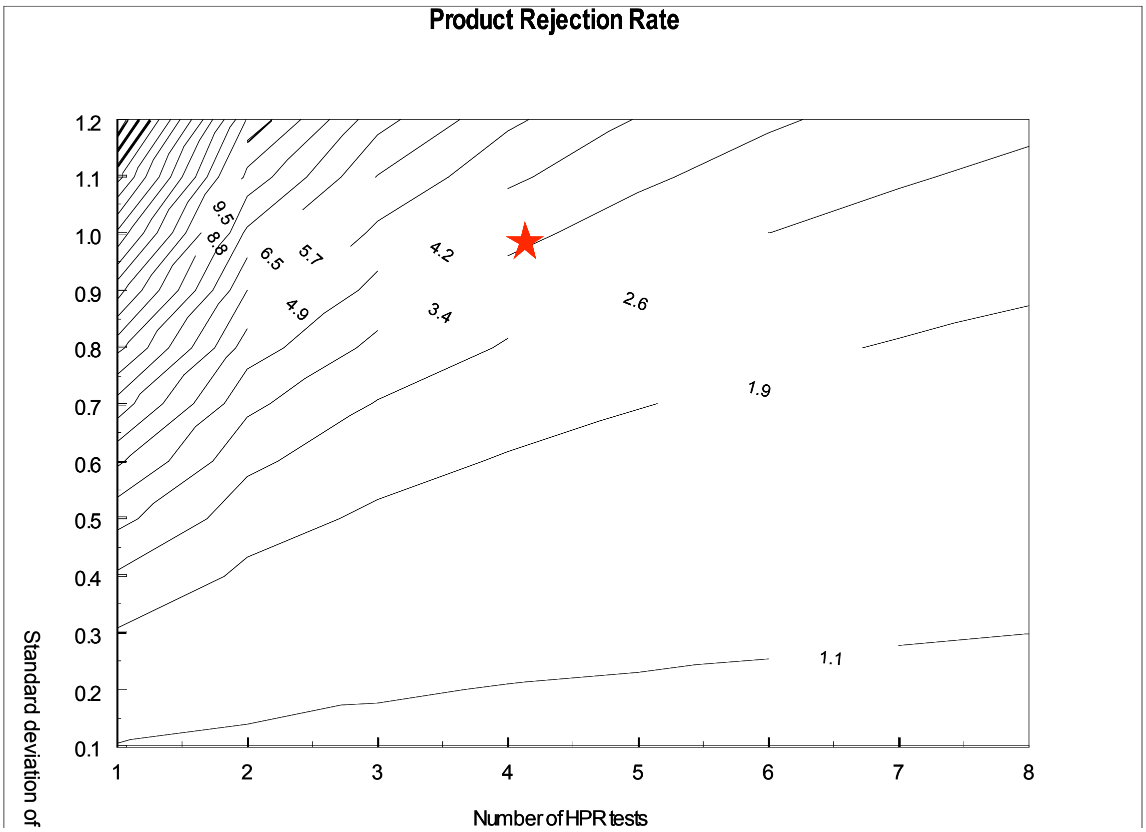


Figure 35 Product rejection rate

4.3.3.4. Improve

The goal of the Improve phase is to fill any system gaps identified during the previous phases and reduce the variability to an acceptable amount. Beyond significant improvements involved with the HPR measurement system, the main focus was to ensure that processes are being performed in a consistent and technically preferred manner. Extensive improvement initiatives were defined and executed. Raw material receiving inspection was enhanced, manufacturing procedure detail was increased, process calculation programs were enhanced, in-process and post-process data gathering was increased, and a new catalyst deposition line was designed and installed. Although the equipment design and procurement was not part of the scope of this program, the resulting process was much improved in terms of both manufacturing consistency (see Figure 36) and overall operating cost.

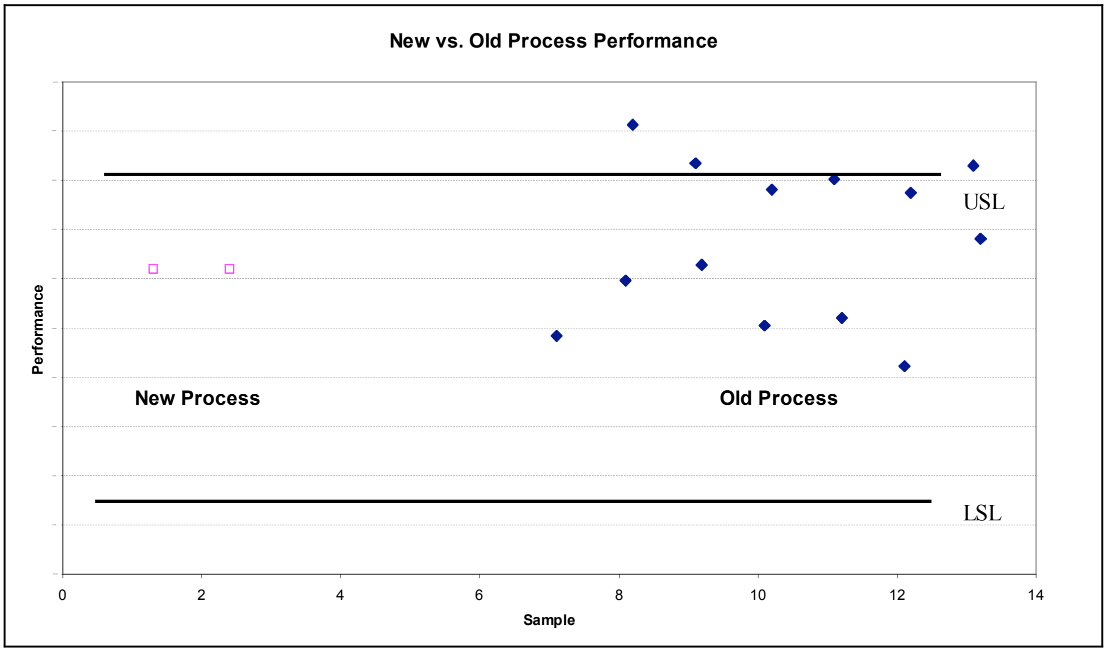


Figure 36 USL = Upper Performance Specification Limit; LSL = Lower Performance Specification Limit

To further reduce manufacturing process variation, key process attributes, defined as those process inputs that significantly impact the key process outputs, must be identified and improved. The first step taken was to identify the attributes of the manufactured product that correlate with the key performance requirements, mainly temperature rise. Significant data were gathered from the study samples and correlation analyses were completed (see Table 4).

	Att 1	Att 2	Att 3	Att 4	Att 5	Att 6	Att 7	Att 8	Att 9	Att 10	Temp Rise
Att 1	1.000										
Att 2	0.070	1.000									
Att 3	0.378	-0.186	1.000								
Att 4	0.231	0.906	0.055	1.000							
Att 5	-0.465	0.341	-0.194	0.516	1.000						
Att 6	-0.332	0.439	-0.341	0.541	0.823	1.000					
Att 7	0.099	0.245	-0.326	0.159	-0.050	0.526	1.000				
Att 8	-0.280	0.591	-0.138	0.754	0.951	0.830	0.028	1.000			
Att 9	0.099	0.245	-0.326	0.159	-0.050	0.526	1.000	0.028	1.000		
Att 10	-0.189	0.640	-0.257	0.747	0.811	0.963	0.473	0.894	0.473	1.000	
Temp Rise	-0.254	0.624	-0.084	0.785	0.922	0.866	0.133	0.989	0.133	0.933	1.000

Table 4 Process correlation results

Several attributes correlated well with temperature rise (for example, 98.9% of temperature rise can be predicted with the value of attribute 8), hence providing focus for further study, in particular a manufacturing performance sensitivity-designed experiment. Initial plans have been developed for this experiment, which is time consuming and expensive.

4.3.3.5. <u>Control</u>

The goal of the Control phase is to ensure methods are in place to maintain the current level of quality and process stability. Many of the improvements instituted were instrumental in ensuring process control, namely manufacturing procedures improvement and increased in-process and post-process data collection. The main on-going elements in assessing process stability are process auditing, and monitoring the process attributes over time using statistical process control charts (see Figure 37). Data are gathered from each production run and action is taken if an out-of-control condition is detected.

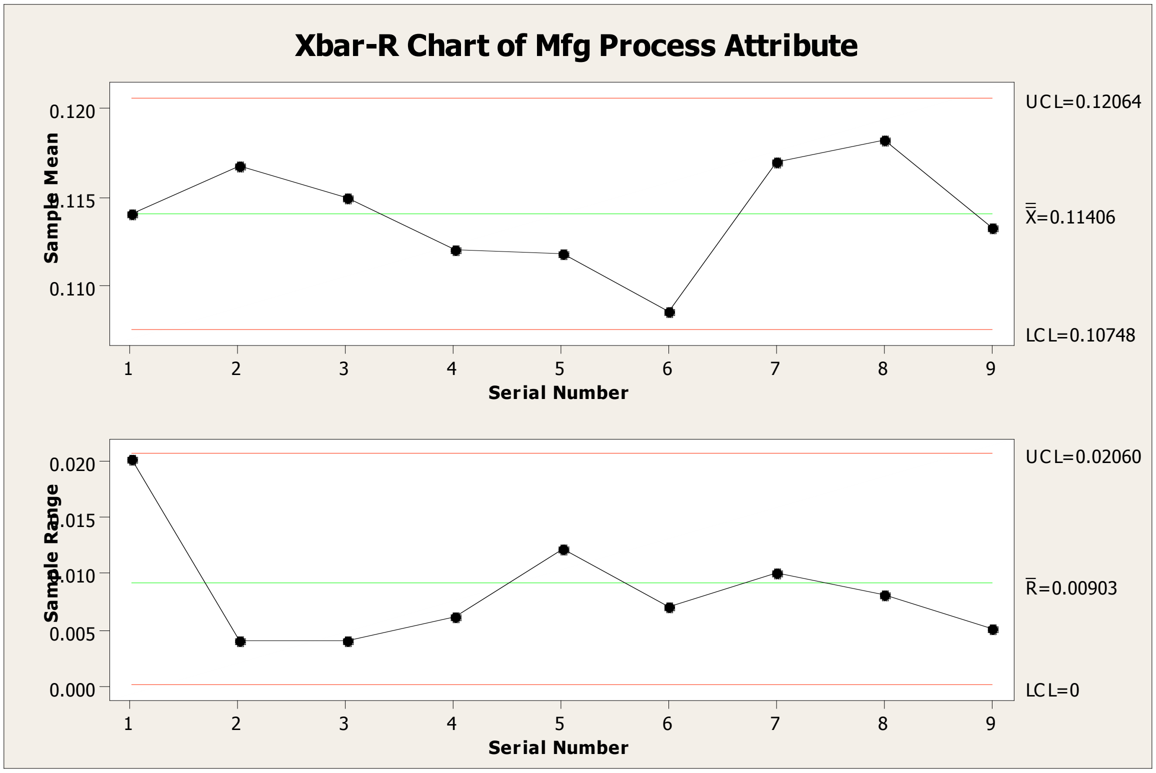


Figure 37 Xbar-R chart of manufacturing process attribute

As the variability in the HPR measurement system is relatively high and the system is utilized to accept/reject product performance, a control plan has also been instituted for this system. A master supply of material was produced. Periodically, material is tested and compared to previous gathered data. As with manufacturing process attributes, out-of-control conditions are investigated and resolved.

4.3.4. Conclusions

Overall, this task was highly successful. The Six-Sigma methodology of Define, Measure, Analyze, Improve and Control was very beneficial in guiding the effort. Detailed process mapping, filling identified system gaps, quantifying process variability, and identifying key process attributes significantly improved product quality and increased the product yield potential from 89% to 97%.

Controls in-place and those to be developed during the continued implementation of the Six-Sigma program will ensure that the current level of quality is maintained, products are produced more consistently, and product reliability is maximized. Future planned design experiments will build upon process knowledge gained through this program, identifying the key process parameters which, when identified and controlled, will yield the most consistent product with the lowest manufacturing cost.

5.0 Conclusions

The primary goal of this project was to extend the application of Xonon to multi-can engine applications. The first phase of the project, in which the enabling technology was developed, has been successfully completed. However, the second phase, which was the engine application portion of the effort, was not completed. After a critical project review prior to commencement of the second phase, CESI and the Energy Commission agreed to halt work on the project. The primary reason for this decision was that CESI was unable to recruit a manufacturer of multi-can gas turbines to join the project for the application phase. After discussions with various original equipment manufacturers CESI determined that the economic and market environment that existed during the course of the project was a detrimental factor contributing to their decisions to not participate.

While the project has ended prematurely, the technical accomplishments of Phase 1 are significant and indicate that the application of Xonon to multi-can engines is feasible. Xonon combustion system size reductions, performance improvements, and advances in control system approaches are some of the key developments realized from this work. CESI hopes that the Xonon technology will yet find its way into multi-can engine applications.

Another accomplishment of the project is the potential yield improvement for the manufacturing process while at the same time increasing product quality. This benefit is directly applicable to the current production of catalyst modules for the Kawasaki M1A-15X which uses the silo-type combustion system configuration. This system is currently operating in California at two sites, with a third under construction.

Glossary

BOZ	-	Combustion Burn-out Zone
CESI	-	Catalytica Energy Systems, Inc.
CL1	-	First Coating Line
CL2	-	Second Coating Line
CO	-	Carbon Monoxide
CPLM	-	Catalyst Performance and Life Model
DLN	-	Dry Low NOx
HPR	-	High Pressure Rig
LCL	-	Lower Control Limit
NOx	-	Oxides of Nitrogen
OEM	-	Original Equipment Manufacturer
ppmv	-	parts per million by volume
SCR	-	Selective Catalytic Reduction
UCL	-	Upper Control Limit
UHC	-	Unburned Hydrocarbon Emissions
Xonon	-	Catalytic combustion technology pioneered by CESI